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ON THE ROLE OF TRAPEZIUS CO-ACTIVITY AND UNFAVOURABLE MOTOR UNIT PATTERNS IN THE DEVELOPMENT OF MUSCLE DISORDERS IN HUMAN-COMPUTER INTERACTION

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Geleitwort

Arbeitsbedingte, muskuloskeletale Beschwerden sind in Europa und auch in der Schweiz eine der häufigsten Ursachen für eine Minderung der Arbeitsfähigkeit bzw. Absentismus. Sie treten nicht nur bei erheblicher Belastung des muskuloskeletalen Systems auf, sondern auch bei Beanspruchungen des muskulären Systems, die deutlich unter der arbeitswissenschaftlich definierten Dauerleistungsgrenze liegen. Epidemiologische Studien haben eine Vielzahl von assoziierten Belastungsfaktoren herauskristallisiert. Dennoch bleibt gerade bei niedrigen Belastungen eine individuelle Prognose unsicher. Manches spricht dafür, daß die individuelle „Programmierung“ einzelner Kompartimente, d.h. verschiedener Motorischer Einheiten eines Muskels in der Pathogenese der Beschwerden eine wichtige Rolle spielt. Diese kann unabhängig von der Aufgabe individuell sehr verschieden sein. Damit kommen die individuellen Unterschiede motorischer Konzepte für die Ausführung einer Aufgabe ins Spiel. Diese Konzepte werden bei einer arbeitsphysiologischen Standardanalyse vernachläßigt, die vor allem auf energetische Aspekte, z.B. das integrale Oberflächen-EMG abstellt. In diesem Sinn reichen Studien, die auf Betrachtungen des Oberflächen-EMG beruhen, nur bedingt für ergonomische Gestaltungsprozesse aus. Nicht mehr die Belastung des Muskels als Gesamtheit ist für die Abschätzung der Beanspruchung motorischer Systeme von Bedeutung, sondern vor allem das Zusammenspiel einzelner Motorischer Einheiten und deren Erholungsverhalten. Das motorische Programm der Koordinierung einer Vielzahl Motorischer Einheiten muß in den Mittelpunkt der Betrachtung gerückt werden. Der Cinderella Hypothese folgend kann es trotz geringer Belastung des gesamten Muskels zu einer Überlast einzelner Motorischer Einheiten kommen, wenn das Wechselspiel der Belastung verschiedener Motorischer Einheiten in einem Muskel nicht gelingt und stattdessen immer dieselben wenigen motorischen Einheiten die Last übernehmen. Zusätzlich muß auch der Koaktivierung von Motorischen Einheiten von Muskeln Beachtung geschenkt werden, die nicht primär für die im Vordergrund stehende Aktivität von Bedeutung sind. Eine solche zusätzliche Koaktivierung zeigen viele Personen bei Fingerbewegungen im Trapezmuskel, selbst wenn dieser beispielsweise bei Tätigkeiten am Computer nicht direkt an der Aktivität der Finger beteiligt sein muß.

Die vorliegende Studie ist ein bedeutender Beitrag zum Verständnis der Bedeutung motorischer Aktivitätsmuster auf der Ebene Motorischer Einheiten für die Beurteilung der muskulären Beanspruchung bei Tätigkeiten mit dem Computer. Sie folgt zwei Haupthypothesen, nämlich:

- Im Trapezmuskel treten bei Computerarbeit stabilisierende Aktivitäten und Koaktivität auf, die von den Aufgaben abhängen, dem Verhalten der Personen und der persönlichen Suszeptibilität.
- Die Koaktivität kann lange anhalten, hat eine geringe Größe, ist unbewußt und anfällig für ein Cinderella-Verhalten.

Die Arbeit ist in den Zusammenhang einer Reihe von Arbeiten zu sehen, die zum Thema am Institut für Hygiene und Arbeitsphysiologie der Eidgenössischen Technischen Hochschule Zürich durchgeführt wurden. Außerdem ist sie nicht denkbar ohne die Europäische Forschungsgruppe PROCID und wichtige Arbeiten des Instituts für Signalverarbeitung der ETH Zürich im Bereich der Signalanalyse. So wurde es möglich, aus dem Oberflächen-EMG sowie dem intramuskulären EMG über längere Zeitabschnitte die Aktivität einzelner Motorischer Einheiten während verschiedener Tätigkeiten zu verfolgen. Die Methodik fand internationale Anerkennung und wird heute in Teilen auch von anderen Forschungsgruppen verwendet. Innovativ ist die Adaptation klassischer physiologischer Methoden an die Anforderungen einer angewandten Forschung mit möglichst praxisnahen Versuchsbedingungen und mit sehr langen Meßperioden.

Die sehr zeitaufwendige, aber erfolgreiche methodische Entwicklung erlaubte in einem exemplarischen Experiment Unterschiede zwischen Maus und Stift als Eingabegeräte in den Dimensionen Leistung, Komfort, Muskelbeanspruchung, zelluläre Beanspruchung gleichzeitig zu untersuchen. Die Ergebnisse sind von großer Bedeutung für den Ablauf motorischer Programme bei realitätsnahen Tätigkeiten am Computer, auch wenn wegen des großen methodischen Aufwandes nur eine kleine Probandenzahl in die Untersuchung miteinbezogen werden konnte.

Die referierten methodischen und experimentellen Ergebnisse stellen einen methodisch sehr hochstehenden und innovativen Beitrag zum besseren Verständnis der Beanspruchung der Muskulatur bei Computerarbeit dar. Der Nachweis der andauernden Aktivität zumindest einzelner motorischer Einheiten im Trapezmuskel ist ein wichtiges Indiz zur Unterstützung der viel diskutierten Cinderella-Hypothese, die Arbeit liefert damit einen wichtigen Beitrag zur aktuellen Diskussion der Genese arbeitsassoziierter muskuloskeletaler Beschwerden. Außerdem zeigt die Arbeit auf, wie die neu eingeführte Methode zur physiologischen Arbeitsgestaltung genutzt werden kann.

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H. Kr

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Zusammenfassung

Hintergrund: Eine Reihe von mechanischen Einflüssen, wie schlechte Sitzhaltung oder unergonomische Tastaturen und Mäuse, werden, neben psychologischen und andern Faktoren, für muskuloskeletale Beschwerden bei Computerarbeit (WRMD, Work Related Musculoskeletal Disorders) verantwortlich gemacht, ohne daß die dahinterliegenden physiologischen Vorgänge im Detail bekannt wären. Die erste Annahme dieser Studie war, daß Oberarm- und Nackenmuskeln mit den Fingerbewegungen koaktiviert werden. Nachdem dies bei einem Teil der Versuchspersonen im Trapezmuskel, Biceps und Triceps nachgewiesen werden konnte, konzentrierte sich der Rest der Studie auf den Trapezius, ein häufig betroffener und dank seiner oberflächlichen Lage für EMG (Elektromyographie)-Untersuchungen auch gut geeigneter Muskel.

Allerdings war die Koaktivitätshöhe, wie man sie bei den meisten Versuchspersonen gefunden hat, so gering, daß sie, nach stundenlangem Fortbestand, allenfalls als Erklärung für eine Muskelermüdung, aber kaum für chronische und degenerative Schmerzen dienen kann. Diese beiden Eigenschaften – kleiner Krafteinsatz, also geringe Zahl eingesetzter motorischer Einheiten (ME), und langer Fortbestand – sind aber die Voraussetzungen für ein neuromotorisches Fehlverhalten, welches Hägg 1991 in seiner Cinderella-Hypothese beschrieben hat. Unter diesen beiden Voraussetzungen soll ein Versagen der ME-Rekrutierungskontrolle eintreten. Einzelne erschöpfte ME werden nicht angehalten, sondern feuern weiter, bis Zellstrukturen zerstört werden und Schmerzen auslösen.

Ziel: Das Ziel der Studie war, Bedingungen zu identifizieren, unter welchen die Oberarm- und Nackenmuskeln koaktiviert werden, und nach Veränderungen im Feuerungsverhalten von ME zu suchen, die mit der Koaktivität in Zusammenhang stehen. Dies führte zu der folgenden Arbeitshypothese:

Nackenschmerzen können durch fortgesetzten Tastatur- oder Mausgebrauch hervorgerufen werden, was zu langandauernder Koaktivität des Trapezmuskels führen kann. Weil die Höhe der Koaktivität gering ist, kann es zu einer Störung des Rekrutierungsmechanismus der ME kommen wie von Hägg (1991) in der Cinderella-Hypothese beschrieben. Diese Störung kann zu Zellschädigungen und Schmerzen führen.

Methoden: Mittels dreier Versuchsreihen wurde die Hypothese überprüft. Die motorischen Anforderungen waren gemischt (leichtere und schwerere Aufgaben wechselten sich ab). Die mentalen Anforderungen waren anfangs klein und die Aufgaben einfach und abstrakt (regelmäßiges Fingertippen). Zum dritten Versuch hin wurden sie vergleichsweise realitätsnah. Alle VP waren gesund, d.h. sie litten aktuell nicht an WRMD (*Work Related Musculoskeletal Disorders*), und rechtshändig. Alle Versuche wurden mit der rechten Hand durchgeführt.

Im ersten Experiment tippten 9 Versuchspersonen (2F, 7M, 29 ± 4 Jahre) mit dem Zeigefinger zu verschiedenen akustisch vorgegebenen Geschwindigkeiten (2, 3, 4, 5 und 6 Hz) während fünf Sekunden auf eine starre Taste (*Tapping*). Zwei weitere Durchgänge wurden ohne akustische Vorgabe mit der maximal möglichen bzw. der als optimal empfundenen Geschwindigkeit durchgeführt. Die identische, randomisierte Reihe wurde je einmal mit aufrechter, vorgelehnter, und zurückgelehnter Körperhaltung durchgeführt. Zuletzt wurde das Langzeitverhalten bei einer Vorgabe von 5 Hz untersucht (Tapping bis zur lokalen Erschöpfung). Als Referenz wurde mehrmals die Muskelaktivität bei entspannter Muskulatur und bei maximal willentlich möglicher Anspannung erhoben (→ Bildung von MVE = EMG-Wert bei maximaler Kontraktion).

Das Ziel des Versuches war es, bei verschiedenen Muskeln zwischen Fingern und Nacken nach Koaktivität zu suchen, während der Zeigefinger einer einfachen, zyklischen Bewegung folgte, und ihre Eigenschaften abhängig von Geschwindigkeit, Haltung und lokalen Ermüdungserscheinungen zu beschreiben. Das Oberflächen-EMG (O-EMG) wurde vom Extensor digitorum communis, Flexor digitorum superficialis, Triceps brachii, Biceps brachii, Trapezius pars transversa und pars descendens registriert; zusätzlich wurde die Tastenanschlagkraft gemessen. Von der (RMS/MVE-)normalisierten EMG-Kurve wurden die 5., 50. und 95. Perzentile als Maß für die statische, mittlere (mediane) und phasische Aktivität berechnet. Mittels der gemessenen Tipprate und Autokorrelationstechniken wurde der Grad der Synchronizität der gefundenen phasischen Aktivität mit der Fingerbewegung beschrieben.

Der Zweck des zweiten Versuches war die Mitarbeit an der Entwicklung eines intramuskulären EMG-Systems mit drei Signalkanälen, Drahtelektroden und hochwertigen Verstärker- und Analysetechniken, sowie die Gewinnung erster Erkenntnisse über das Feuerungsverhalten von koaktivierten motorischen Einheiten. Bei 6 Versuchspersonen (3F, 3M, 33 ± 7 Jahre) wurde das Muskelverhalten bei der Arbeit mit dem Zeigefinger auf dem Zahlenblock einer gängigen Computertastatur untersucht. Die Aufgaben von je drei Minuten Dauer waren: Tapping auf einer Einzeltaste zu akustisch vorgegebenen 5 Hz, Eingabe von dreistelligen Zahlen mit dem Zeigefinger (durch eine Audioaufnahme im Abstand von 2 Sekunden vorgespielt) sowie vollständiges Entspannen mit geschlossenen Augen. Mittels selbst hergestellter Vierdrahtelektroden wurde die Trapezmuskelaktivität im pars descendens dreikanalig intramuskulär gemessen. Da zu diesem Zeitpunkt noch kein geeignetes Zerlegungsprogramm für dreikanaliges intramuskuläres Langzeit-EMG (I-EMG) zur Verfügung stand, wurden mehrere Kurzzeit-/1-Kanal-Analysen von Hand und mithilfe eines MatLab®-Skripts zu einem Feuerungsverlauf kombiniert.

Im dritten Experiment wurde der Frage nachgegangen, ob sich (a) im Feuerungsverlauf einzelner ME ein von Koaktivität beeinflußtes Muster aufzeigen läßt, ob (b) in koaktivierten ME Cinderella- oder andere auffällige Verhaltensmuster auftreten, (c) was für Zusammenhänge zwischen den O- und I-EMG Parametern bestehen, um herauszufinden, ob das O-EMG für die Identifikation von gefährlichem ME-Verhalten geeignet sei, und (d) ob die verschiedenen Ergebnisse durch den Gebrauch zweier Zeigegeräte (Maus und Pen/Tablett), welche unterschiedliche Fingermechaniken voraussetzen, beeinflußt werden. Die einzelnen Bedingungen wurden auch hinsichtlich der subjektiven Anstrengung und Schmerzen, sowie der gemessenen Performance untereinander verglichen.

Während der neunminütigen Aufgaben sollten die neun Versuchspersonen (32 ± 5 Jahre) auf verschiedene Objekte auf dem Bildschirm klicken, doppelklicken oder sie mit dem Zeigegerät verschieben. Dreikanaliges I-EMG wurde vom Trapezius pars descendens mit Drähtchenelektroden abgeleitet und mit EMG-LODEC (automatisierte, dreikanalige Zerlegungssoftware) analysiert. Die früheren Resultate zu Koaktivität wurden mit eventgetriggerten O-EMG-Überlagerungen und mit Kumulativsummen des Feuerungsverlaufs des I-EMG validiert.

Resultate: Mittels O-EMG konnte Koaktivität des Trapezmuskels in allen Versuchen festgestellt werden, doch gab es stets auch Personen ohne meßbare Aktivität oder in einer Höhe, die sich nicht von der bei Ruhe unterschied. Selten wurden allerdings Werte über 5% MVE gemessen. Bei manchen Versuchspersonen wurde auch unter günstigen Bedingungen und bei bewußter Entspannung eine Oberflächenaktivität (im Bereich <1% MVE) und aktive ME festgestellt. Ein vorgegebenes, hohes Arbeitstempo verstärkte beim ersten Versuch die Koaktivität, ein vorgegebenes, langsames Tempo hatte eine mittlere, und ein frei gewähltes, mittleres Tempo eine geringere Koaktivität des Trapezmuskels zur Folge. Sie war außerdem stärker bei einer vorgebeugten und etwas schwächer bei einer zurückgelehnten Haltung, verglichen mit dem aufrechten Sitz. Verschiedene Autokorrelationshöhen des Zeitverlaufs des O-EMG (Lag = Tipprate) zeigten, daß die gemessene Koaktivität manchmal eng mit der Fingeraktivität zusammenhängt, manchmal jedoch ziemlich unabhängig davon verläuft. Auch der Anteil konstanter Aktivität war sehr unterschiedlich.

Im zweiten Versuch wurden aktive ME bei Ruhe in 1 (wovon 0 kontinuierlich), bei Zahleneingabe in 2 (2) und beim Tapping in 5 (1) Versuchspersonen gefunden. In Versuch 3 wurden in der Hälfte der Ruhemessungen und in einer Mehrzahl der anderen Messungen aktive ME identifiziert. Bei Ruhe fanden sich keine, bei der Arbeit mit der Maus 7 und mit dem Pen 11 kontinuierlich aktive ME. Bis auf eine wurden diese bei genau zwei Individuen festgestellt.

Wiederum konnten einige VP die Aufgaben ohne meßbare Trapezmuskelaktivität ausführen, während andere diesen selbst während Ruhemessungen anspannten. Das Überlagern der O-EMG-Kurven zeigte zuweilen ein deutliches Abbild der Fingerbewegung im Trapez. Kumulativsummen ließen klar einen Wechsel des Feuerungsverhaltens einzelner ME erkennen. Solche Beobachtungen wurden vor allem mit der Maus, aber kaum mit dem Pen gemacht. Doubletten wurden während der meisten Trials entdeckt; teilweise war ihre Anzahl außergewöhnlich hoch (bis zu

über 30% aller Feuerungen). Konstante Aktivität von ME (Cinderella) wurde in 18 von 54 Trials (exkl. Ruhe-Trials) gefunden. Zusammenhänge zwischen O- und I-EMG-Parametern konnten nicht identifiziert werden.

Oberarme und Finger: Die Messung des O-EMG der Oberarmmuskeln (Versuch 1) ergab zumeist eine geringe Aktivität (außer manchmal bei maximaler Tippgeschwindigkeit oder kurz vor Abbruch beim Langzeit-Task). Bei manchen VP konnte auch hier eine gewisse Synchronisation mit der Fingerbewegung festgestellt werden. Bei den Fingern wurden langsame Bewegungen ohne Flexoreinsatz durchgeführt; bei mittleren Tempi beteiligte sich der Flexor kooperativ-antagonistisch und bei hohen Tempi kompetitiv-antagonistisch (gleichzeitig aktiv) zum Extensor.

Performance und Anstrengung: Bei der Langzeitaufgabe von Versuch 1 konnte kein Zusammenhang zwischen den verschiedenen Parametern des O-EMG und der Dauer bis zum Versuchsabbruch gefunden werden. Beim zweiten Versuch empfanden die Teilnehmer das Tapping als anstrengender als die Eingabe von Zahlen. Die Performanceberechnungen von Versuch 3 zeigten einen signifikanten Geschwindigkeitsvorteil für den Pen, obwohl dessen Gebrauch nur eine halbe Stunde geübt worden war. Doppelklicken war sowohl mit der Maus als auch mit dem Pen signifikant langsamer als Einfachklicken. Die mit Fragebogen erfaßte Anstrengung war mit dem Pen bei den meisten Vergleichen signifikant geringer.

Schlußfolgerungen: Es wurde gezeigt, daß bei intensiver Arbeit mit Computereingabegeräten der Trapezmuskels häufig und unnötigerweise koaktiviert wird, und daß die Koaktivität stark von Bedingungen wie Eingabegerät oder Geschwindigkeitsvorgaben abhängt. Es wurde ebenfalls gezeigt, daß während 9-minütiger Arbeit mit einem Zeigegerät ununterbrochene Aktivität einzelner ME (Cinderella-Verhalten) auftreten kann. Die Cinderella-Therorie basiert auf der Aktivität von wenigen ME, deren Beitrag im O-EMG sehr klein sein mag. Das O-EMG, das die Gesamtaktivität des Muskels wiedergibt, kann also nicht zur Auffindung von gefährlichem ME-Verhalten dienen. Für eine sorgfältige Identifikation von Arbeitsbedingungen, die Cinderella-Verhalten fördern oder hemmen, muß die I-EMG-Technik auf Aufnahmezeiten von mehreren Stunden ausgedehnt werden (wobei die Elektroden nicht verschoben werden dürfen, so daß dieselben ME während langer Zeit beobachtet werden können).

Aufgrund der Fähigkeit einiger VP, die Aufgaben auch ohne Einsatz des Trapezius auszuführen, kann vermutet werden, daß betroffene Personen von einer neuromotorischen Schulung profitieren sollten, wo sie lernen, ihre Bewegungsmuster so anzupassen, daß der Computer ganz ohne Nackenkoaktivität bedient werden kann. Manche Versuchspersonen waren selbst mit geschlossen Augen und ohne die Anwesenheit anderer Personen oder von Störungen im Raum nicht in der Lage, auf dem Bürostuhl eine vollständige Entspannung der Nackenmuskulatur herbeizuführen. Während normalen Arbeitspausen wird diese wohl auch im Betrieb nur schwer erreicht. Entspannungstechniken müssen gelernt werden, wenn das

Loslassen des Nackens nicht im bewußten motorischen Repertoire des Individuus liegt. Koaktivitätsverringernd scheinen eine entspannte Arbeitshaltung, ein lockeres Arbeitstempo und der Einsatz eines Pens anstelle der Maus zu sein. Mit letzterem ist gleichzeitig ein höherer Arbeitsdurchsatz ohne Erhöhung der Anstrengung möglich.

Abstract

Background: A series of mechanical factors, such as constraint body postures or unergonomic input devices are, next to psychological and other factors, regarded causative in the development of work related musculoskeletal disorders (WRMD) with computer use, without knowing in detail the underlying physiological processes. The first assumption of this study was that the muscles of the upper arms and neck can be co-activated with the finger movements during computer use. After having confirmed this assumption for the invested muscles with a part of the subjects during a first experiment, the remainder of the study focused on the trapezius muscle, which is a frequently affected muscle and, in addition, is practical for EMG (electromyographic) investigation due to its superficial location.

The levels of co-activity were, however, low in most subjects. Even if it is feasable that such low levels could cause muscle fatigue if going on for many hours, they can't explain chronic and degenerative pain symptoms. It's these two characteristics – little force requirements, thus small number of activated motor units (MUs), and long persistence – that Hägg assumed requirements for a neuromotor malfunction described in 1991 in his Cinderella hypothesis. Some exhausted MUs would not be suspended, but continue firing until muscle cell structures take damage and cause pain.

Aim: The aim of the study was to identify conditions that lead to co-activity of the neck and upper arm muscles and to investigate any changes in MU firing behaviour in connection with co-activity. It was hypothesised that

Neck pain may be initiated by the ongoing use of input devices causing trapezius muscle co-activity during extended periods. Since the co-activity levels are low, the motor unit recruitment control may fail as described by Hägg's Cinderella hypothesis (1991). Such failure would lead to cell damage and pain.

Methods: The hypothesis was verified with the aid of three experiments. The motor demands were mixed (alternation of simple and difficult tasks). The mental requirements were less demanding initially and the tasks simple and abstract (regular finger tapping). In the third experiment the tasks became more real-life oriented. All subjects were healthy, i.e., did not currently suffer from WRMD (work related musculoskeletal disorders), and right-handed. All experiments were conducted using the right hand.

9 subjects (2F, 7M, 29 ± 4 years old) were instructed in the first experiment to tap with their index finger on a rigid key, at a series of predetermined rates (2, 3, 4, 5 and 6 Hz, by an electronic metronome) during five seconds. During two additional trials without the metronome the subjects tapped at their individual, highest possible rate, and at a rate that they rated optimal. The identical, randomised series was completed assuming an upright, then a leaning forward, and finally a slightly reclined position.

Finally the long-term behaviour was investigated with a predetermined tapping rate of 5 Hz (tapping until exhaustion). The muscle activity with relaxed muscles and with maximum voluntary contraction was assessed several times for reference (→ formation of the MVE = EMG at maximum voluntary contraction).

The aim of the experiment was to find, with the cyclic finger tapping, co-activity patterns in different muscles between the fingers and the neck, and to describe their properties depending on alterations of speed, posture and fatigue-related conditions. The surface EMG (S-EMG) was measured from the extensor digitorum communis, flexor digitorum superficialis, triceps brachii, biceps brachii, trapezius pars transversa and pars descendens), together with the force on the key. The 5th, 50th and 95th percentiles of the RMS/MVE-normalised EMG were determined and used to describe static, median and phasic activity, respectively. The amount of synchronicity of measured phasic activity and finger movements was describd by auto-correlation and measured tapping rate.

The purpose of the second experiment was to help develop an intramuscular EMG system with three signal channels, wire electrodes, and high-class amplification and decomposition skills (developments at ETH), alongside with gaining first insights in the firing properties of co-activated MUs. The muscle behaviour of six subjects (3F, 3M, 33 ± 7 years old) was examined with tasks that involved the index finger working on the numeric keypad of a standard keyboard. The tasks lasted three minutes each and included: tapping on a single key with the index finger at 5 Hz (by an electronic metronome), entering of 3-digit numbers with the index finger (presented through an audio recording at a rate of 2 seconds), and complete relaxation with closed eyes. Own wire electrodes, manufactured with four fine wires, were used to measure a three channel intramuscular EMG (I-EMG) of the trapezius pars descendens. As a suitable decomposition programme to analyse the long-term, three-channel I-EMG was not yet available, three single analyses by MAPQUEST were combined to one firing sequence by hand, supported by a MatLab® script.

The third experiment was set up to see if, by I-EMG, (a) patterns can be found in MU firing trains that have been provoked by co-activity, (b) to verify if co-activated MUs show Cinderella or other conspicuous behaviour, (c) to search for links between the parameters of the surface and intramuscular EMG in order to clarify if S-EMG can serve to identify hazardous MU behaviour, and (d) to test if any of these findings will be influenced by using two pointing devices that require different finger mechanics (mouse and pen/tablet). All conditions were also compared concerning the perceived effort and pain and the measured performance.

The tasks included clicking, double-clicking and dragging-&-dropping with various objects on the screen and were conducted with nine healthy subjects (32 ± 5 years old). Each task lasted 9 min. Three-channel I-EMG was recorded from the trapezius p. descendens with wire electrodes and analysed with EMG-LODEC (automated 3-channel decomposition software). The analysis duration could be expanded to 9 minutes. The previous findings on co-activity were validated with event-triggered I-EMG superpositioning and cumulative sums on the I-EMG.

Results: Trapezius muscle co-activity was found by S-EMG in all experiments, though there were always a number of subjects without detectable activity, or levels similar to that with relaxation. Levels over 5% MVE were, however, rarely seen. With certain subjects surface activity (in ranges < 1% MVE) and active MUs could be recorded even during conscious relaxation. In the first eperiment, a pre-determined, fast working pace was associated with a higher, a pre-determined, slow pace with a medium, and a self-determined, medium pace with a lower level of trapezius co-activity. The levels were higher when leaning forward and somewhat lower when slightly reclined, compared to the upright posture. Different amounts of S-EMG autocorrelation magnitudes (lag = tapping rate) disclosed that measured co-activity may be closely linked to the finger's activity in some, but unrelated in other cases. The amount of constant activity varied as well.

In the second experiment active MUs were found in 1 (whereof 0 continually) subjects with resting, in 2 (2) subjects with inputting numbers, and in 5 (1) subjects with tapping. In experiment 3, active MUs were seen in half of the relaxation trials and in the major part of the other trials. Continuously active MUs were not seen with relaxation. 7 continuously active MUs occurred with mouse and 11 with pen tasks. All of them but one were found in two specific subjects.

Again, some subjects could complete the working trials with no measurable trapezius activity while others could not release the muscle even during the relaxation trials. S-EMG superpositioning showed, in the trapezius, some marked images of the finger movement. Cumulative sums showed clearly a change in firing behaviour of specific MUs. These observations were made with the mouse, but hardly with the pen. Doublets were found in most tasks, but in some their number was extremely high (up to over 30% of all firings). Ongoing MU activity (Cinderella) was seen in 18 of 54 trials (excluding relaxation trials). Correlations between surface and intramuscular EMG parameters were not found.

Upper arms and fingers: The S-EMG recordings of the upper arm muscles (exp. 1) revealed a mostly low levelled activity (except, sometimes, at the highest possible tapping rate, or shortly before exhaustion in the long-term trial). A certain amount of muscle synchronization with the finger movement was observed in some subjects. The fingers were used without flexor activation with slow movements; with medium rates the finger flexor and extensor established a co-operative antagonism, whereas with high rates the antagonism became competitive (muscles acting simultaneously).

Performance and effort: No relationship could be found between the S-EMG parameters and the duration until exhaustion in the long-term task of experiment 1. The tapping task was rated more strenuous than the inputting of numbers (experiment 2). Despite limited training (half an hour), the clicking performance in experiment 3 turned out to be significantly higher with the pen than with the mouse.

Double-clicking was significantly slower both with the mouse and with the pen, compared to single clicking. The effort was rated significantly lower with the pen in most comparisons.

Conclusions: It could be shown that, with intensive computer input device use, the trapezius muscle is often, and unnecessarily, co-activated, and that conditions such as the input device or speed requirements have a significant influence on co-activity. It could also be shown that with 9-minute pointing tasks ongoing activity of single MUs (Cinderella behaviour) can occur. The Cinderella theory is founded on the fact that the number of involved MUs is low, the electric account of which can be very small in the S-EMG. The total activity as reported by the S-EMG would thus not be of revelance regarding dangerous MU behaviour. For a detailed identification of work conditions that favour or impede Cinderella behaviour, I-EMG recordings must be extended to several hours (without displacing the electrode so as to observe the same MUs during extended periods).

Seen that some subjects were able to complete the tasks without the need to involve the trapezius it is feasable that affected persons should profit from neuromotor (re-) education, improving their motor patterns such that neck co-activity can henceforth be avoided entirely with computer use. Achieving full relaxation of the neck musculature while sitting in the office chair was not possible for some subjects even with closed eyes and no disturbance or any other person being present in the room. Normal work breaks may be insufficient for such individuals at the workplace. Relaxation techniques need be learnt if relaxing the neck is not within an individual’s conscious motor repertoire. A relaxed working posture, stress-free working pace, and replacing the mouse by a pen with tablet seem to reduce co-activity. With the latter work performance can even be augmented without increasing the perceived effort.

1 Practical implications

Compared to most industrial and manual professions, the necessary muscle force is low in occupations with computer use. Nonetheless the prevalence of work related musculoskeletal disorders (*WRMD*) with pain in hands, arms, shoulders and neck is high above average in humans working in these occupational fields. Computers are governing life to an ever greater extent. Not only at work are they predominating more and more, but also at our leisure activity – particularly regarding teenagers and children. The number of affected persons is likely to increase massively in the next years. Usually, pain takes several years of exposition to set in, but then often gets chronic and resistant to treatment. It is therefore crucial to emphasise early prevention. Due to the high medical, but also operational costs owing to employees on sick leave, this would also make economic sense.

1.1 Missing thresholds

Although many risk factors are known in the context of computer use (though not their damaging thresholds), scientific knowledge on the mechanisms behind the development of WRMD is limited. Such knowledge would be useful as a base for the formulation of thresholds, guidelines, regulations for the design of input devices and other preventive measures, which have existed for a long time for other occupational fields. Present guidelines for computer work are mainly based on empirical data rather than physiological findings. It was therefore the aim of the research reported in this thesis to find, by means of electromyography, unusual motor behaviour in the affected muscles (especially the trapezius) during computer use, and to identify favourable and unfavourable conditions to provoke such behaviour.

1.2 The co-activity and Cinderella hypotheses

Instead of investigating generally assumed factors like bad posture or neck contraction due to missing motion, the origin of the disorders was postulated to lay in the finger movements themselves – a secretary may perform 100.000 keystrokes, a CAD or graphics designer click the mouse buttons several thousand times each day. The investigated assumption was a) that parts of the trapezius muscle are being activated in conjunction with the finger movements (*co-activity hypothesis*), and b) that the activity of some of these co-activated muscle fibres is not suspended, despite their being (physiologically) exhausted, until degenerative processes and pain set in (*Cinderella hypothesis*).

The Cinderella hypothesis (Hägg 1991) explains the failure of control based on two conditions, which are both met here: 1) the level of force and thus the number of active muscle fibres must be low compared to the muscle's capacity, and 2) the force demand must persist for extended periods. Pain would thus be owed, in a way, to a neck 'understrain' and not an overstrain.

Co-activity was often found in the trapezius muscle, differing in amount and type. It was generally reduced with a self-determined (vs. predetermined) work speed, with sitting relaxed and slightly reclined, and by pointing actions (single-/double-clicking and drag-and-drop) performed with a pen instead of a mouse. Ongoing activity of muscle fibres (Cinderella hypothesis) was found in a couple of subjects during nine minute data collections. One of the relevant findings is that the same tasks could be accomplished by some subjects without involving the trapezius muscle at all. This means that other persons should be able to learn how to motorically improve their typing and pointing style. Some subjects did not achieve complete neck relaxation when instructed to do so. Relaxation techniques should be learnt by these individuals. Normal work breaks may be insufficient to release the tension in the neck.

1.3 Trapping the mouse

Despite limited training (30 minutes) the pen was superiour in comparison to the mouse regarding performance (pointing actions per minute), while the perceived effort, which the subjects indicated by questionnaire, was reduced. The hand's deviation from the neutral position and the required forces are smaller with the pen. Clicking, e.g., is achieved by touching the tablet surface with the pen tip. Unfortunately, first-time pen users (outside the laboratory) often do not manage to operate it correctly due to lacking instruction. It can be observed that persons who are in fact using a pen were in most cases so badly affected by mouse-related WRMD that they could not have remained in their current job. It would be desirable that pen manufacturers include proper instructions and training software with their devices.

To make pen usage even more efficient, the tablet could be equiped with a suspension (e.g. by magnets) so that the pen would be hovering centimeters above the tablet while not in use, and grasped more rapidly. This would make work smoother especially with frequent switching between keyboard and pen. The rather new concept of the *Tablet PC* could help spread the usage of the pen. Here a pen is operated directly on the flat monitor. However it is possible that the large tablet would be used with an elevated hand, which could lead to strain in the shoulder.

1.4 Co-activity, coordinated movements and motor learning

The connection between trapezius co-activity during input device usage, and co-activation as a coordinative and integrative contribution to any kind of movement – fundamental in the motor concepts of neurophysiologists like Nikolai Bernstein or Moshe Feldenkrais – is unclear. According to their concepts, a ‘well’ learnt, smooth and ‘easy’ movement is not realised with an isolated limb, but with finely tuned co- and counter-movements of a multitude of muscles, taking advantage of gravity and the physical properties of the body’s spring-mass system. This way the strong trunk muscles, originating at the spinal column, can support the smaller arm, leg and head muscles in every situation and make all movements smooth and easy.

Unfortunately a spinal column forced to immobility in an office chair does not really possess much liberty of action. But aside from that, most modern citizens’ actual motoric use of the body is very much limited and stays far from its capabilities. Feldenkrais (1904-84) attributes this to emotional and thinking patterns, impressed and internalized since early childhood, that are reflected in corresponding movement and posture patterns. Parasitic tensions are working against our intended movements. He can show a strong relationship between psyche and motor activity. Beside poor performance and the feeling of strain, this can also lead to unnecessary wear and tear of tendons, joints and intervertebral disks. The continuous strain, at least as long as it has not caused serious injury, is often not even perceived consciously, because many individuals have never, since early childhood, experienced the effortlessness of body usage without permanent unconscious parasitic motivations, expressed as strain. Alternatively, the facts are recognized and accepted as the will and intention of God or Nature. Motor control can however be re-learnt (e.g. Feldenkrais 1949 and 1999). Depending on the amount of personal deficiency such learning can be accomponied by important, positive psychic changes, because mental and motor blockades have strong connections.

2 Background

Work related musculoskeletal disorders (WRMD) of the neck, shoulder and upper limbs have a high and increasing prevalence in connection with computer work. Despite long-time research their exact etiology could not be clarified. This chapter gives an overview of the most important research and theories in this field during the last years and describes the main strain factors occurring with typical keyboard and pointing device use.

2.1 Prevalence of WRMD in human computer interaction

Work related musculoskeletal disorders (WRMD) of the neck, shoulder and upper limbs (often used in equivalence with the term ‘repetitive strain injuries’, RSI) are a major health risk in human-computer interaction (HCI) (Hagberg and Wegman, 1987, Kuorinka et al, 1995, Läubli and Krueger, 1992). Known harmful factors are prolonged immobile sitting with static and constrained postures of the head, shoulders and upper limbs, neck flexion, bad workstation ergonomics (desk, chair, screen, input devices, computer noise, light reflections), task invariability, mental and visual stress and psychosocial factors. Repetitive finger and arm movements of low load have been shown to be a key factor in the etiology of WRMD (Maeda 1977).

With the ongoing substitution of traditional work by computers and their increasing use also during leisure time it is likely that the prevalence of disorders will rise even more. The rising use of computer mice may constitute an additional risk. WRMD often take years of exposure to develop and are likely to become chronic. The individual’s re-integration into the work process is, despite treatment, often unsuccessful.

The exact characterisation of WRMD in HCI is difficult and often termed ‘unspecific’, compared with more 'specific' disorders of the upper limb (e.g. carpal tunnel syndrome, de Quervain's disease of the wrist, radial epicondylitis, shoulder capsulitis, or shoulder tendonitis), where rather good consensus in case definitions exists (Harrington et al 1998). Hagberg (1996) gave a definition based on history (gradually increasing pain and stiffness during the working day and week, localised to cervical spine and angle between neck and shoulder, improved by heat and worsened by cold draughts, no radiation of pain), signs (tenderness over neck and shoulder muscles, reduced range of active movement of cervical spine but normal passive movement, no neurological deficits) and exclusion of differential diagnosis like nerve entrapments and systemic diseases.

Although a relationship between prolonged work with computers and WRMD is scientifically established, the exact causality is not fully understood. It is for certain multifactorial and includes, apart from the factors mentioned, also individual susceptibility and behaviour. Little is known about interferences of these risk factors (Hagberg 1996). The unspecific characteristics and unclear causality aggravate the formation of effective prevention strategies, including recommendations concerning ergonomic design of input devices. Existing guidelines are often based on subjective experience, empirical data and performance assessment instead of physiological knowledge. Further research investigating the physiological mechanisms in the pathogenesis of WRMD is crucial.

2.2 Pathophysiology of WRMD

Not only the characterisation and causality of WRMD provoked by computer work, but also the underlying pathophysiological changes are not completely clear.

Older models were based on the fact that muscle contraction can inhibit the blood flux within the muscle (Rohmert 1965). However this holds for static levels above about 15% of maximum voluntary force, which is not normally achieved in human-computer interaction.

Early research in Japan by Maeda (1977) has brought up the concept of ‘local fatigue’ in the muscle. In Japan, WRMD of the neck and upper limbs are known as ‘occupational cervicobrachial disorders’ and have been described e.g. in operators of punch cards (Komoike 1971), accounting-machines (Maeda et al 1980) or cash-registers (Nakaseko 1985). Maeda’s ‘local fatigue’ concept emphasised the importance of the combined strain from different factors such as repetitive finger movement, long working hours, psychological stress and room climate, leading to local muscle fatigue, pain, and the start of a vicious circle (pain – nociceptive reflexes – more muscle tension and pain – interrupted sleep and insufficient recovery at night – more effort to compensate for missed sleep – more muscle tension and pain). This concept led to a successful introduction of preventive measures in Japan (Maeda et al 1982). However the questions remained unanswered, what exactly ‘local fatigue’ is, and why pain receptors would be activated.

Muscle cell damages such as described e.g. by Friden (1981) as myofibrillar disturbances following eccentric contraction, especially with regard to the Z-bands, or long-lasting increased serum creatinine kinase after heavy work found by Hagberg et al (1982), which he hypothesised being a predictor for work related muscle strain, can’t explain the processes in typical computer work, because the findings related to heavy physical exertion with high oxygen consumption.

In the 1990’s, biopsy studies from the trapezius muscle revealed a lower capillary-to-fibre area ratio in patients with chronic pain compared to healthy controls (Lindman et al 1991), so that local blood flow may be reduced, resulting in an early onset of fatigue. Decreased blood flow was indeed measured in settings with low level physical activity in subjects with chronic myalgia (Lund et al 1986, Larsson et al 1990, 1994). Following Mense (Mense 1991), such disturbance in microcirculation may sensitise nociceptors so that even small stimuli can evoke pain. The question remains open, if these disturbances are primary or secondary to chronic pain.

Johansson and Sojka (1991) introduced a pathophysiological model which also might clarify why chronic pain conditions have a tendency to perpetuate themselves and spread from one muscle to another. In this model, metabolite accumulations produced by static muscle contractions with reduced blood flow stimulate group III and IV muscle afferents, which activate γ motor neurons projecting to both agonistic and antagonistic muscles. The γ motor neurons influence the stretch sensitivity and discharges of secondary and primary spindle afferents. Increased activity in the primary muscle spindle afferents enhances the muscle stiffness, which leads to further production of metabolites in both agonistic and antagonistic muscles. Increased activity in secondary spindle afferents, which project back to the gamma system, constitutes a second positive feedback loop which may perpetuate the condition with stronger contractions and stiffness. But this model was refuted by Lund et al (1991) who explained that most studies could not demonstrate hyperactivity of the muscles involved.

Using surface EMG, Elert et al (1989) reported that patients with fibromyalgia had a larger EMG amplitude during passive extension in the neck and deltoid muscle. In a laboratory study simulating light repetitive work, electromyographic signs of fatigue were observed both in the cervical and lateral part of the descending trapezius muscle (Sundelin and Hagberg 1992). The muscle fatigue was less pronounced when pause activities were introduced into the work (Sundelin 1993). Elert et al (1991) reported an inability to relax myalgic trapezius muscle in patients with work-related myalgia and an inability to relax in all registered muscles in patients with fibromyalgia using surface EMG during a laboratory experiment with a repetitive task compared to healthy subjects. But the groups differed neither in mechanical performance nor in fibre type proportions. Vasseljen et al (1995) registered the trapezius muscle activity in office and manual workers. The subjects showed significantly increased trapezius muscle activity and fewer ‘gaps’ (substantial decrease of surface EMG level during no more than a few 100 ms) than the controls in manual work. In contrast to this, in office work muscle activity of the cases and the controls did not differ. These results support the hypothesis of increased muscle activity and reduced periods of full relaxation in cases with manual work, but not in cases with office work. Veiersted et al (1993) showed in a prospective study with 30 healthy female employees of a chocolate manufacturing plant that future patients had a lower frequency of EMG gaps than non-patients. However the authors suggested that gaps may not be the optimal parameter for the characterisation of prolonged muscle activation due to repetitive work. Jensen et al (1999) found considerably fewer gaps during CAD work in the ipsi-lateral part of the trapezius muscle than in the contra-lateral part and associated the lack of EMG gaps with the development of disorders.

Seidel and Bräuer (1988) and Hägg (1991) postulated the so-called ‘Cinderella hypothesis’, an interesting model based on the size principle of Henneman (ordered recruitment of motor units (MUs) with increasing force; Henneman 1965). It assumes that in low-load contractions certain type I muscle fibres (so-called C-fibres) with low threshold are active during prolonged time and until total relaxation of the muscle, possibly during a whole working day. The naming refers to the tale of Cinderella, who was the first in the morning to start work and the last to go to bed. Even when such fibres are exhausted, their substitution (as claimed by Person, 1974) would not occur, because the total muscle load, the number of fibres involved and the overall accumulation of metabolites (potassium) in the insterstitium are too low to mediate local exhaustion to the central nervous system. Overload of the fibres may cause functional disturbance of the cell membrane, so that intracellular substances can leak into the interstitial space and activate pain receptors, which would be the starting point in the development of chronic muscle pain[1]. Some studies on morphological changes in the trapezius muscle of myalgic patients found indications supporting this hypothesis (Larsson SE et al 1988, Lindman et al 1991), while another group could not confirm it (Larsson B et al 1992). A relatively fixed MU recruitment pattern during low level dynamic contractions in the biceps muscle was described by Søgaard (1995) using intramuscular EMG. In contrast to this, Fallentin (1993) found a time dependent MU recruitment pattern in isometric low level contractions.

Westgaard and De Luca (1999) described MU substitution in the trapezius muscle during contractions of 10 minutes (either static contraction, manipulation task with mental concentration, or typing) and found substitution after some minutes that often coincided with a short period of inactivity in the surface EMG pattern. Gaps can therefore be seen as indicators for MU substitution (or rotation).

Until recently, EMG techniques were either used to study the force development (surface EMG) or pathological changes resulting in a shape change of the action potential (intramuscular EMG). The tracking of the activity of MUs during periods longer

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[1] During the activity of large muscle parts, potassium (K^+) concentration in the interstitium will increase due to repeated activation of the muscle fibres, and the excitability of the muscle fibres will decrease. This can be seen as a natural protective mechanism against overload. Depending on the metabolic requirements, K^+, together with Ca^{2+}, is involved in the regulation of the blood flux in the muscle. During the activity of only single muscle fibres the K^+ ions leaving the cell will be diluted and removed by the blood stream. This way no stimulus is generated that would signal fatigue of the fibre, and the membrane excitability will not decrease. With ongoing activation and metabolic exhaustion the function of the membrane will eventually be disturbed and proteins and other substances can leave the cells and trigger pain receptors in the interstitium. Thus, with repeated activation of single motor fibres their exhaustion is not perceived until pain emerges. Hence, protective mechanisms against overload during repetitive low-intensity contractions are insufficient. (Sjøgaard and McComas 1995, Sjøgaard 1996)

than a few minutes in order to find C-units was not possible due to technical limitations. Developments such as EMG-LODEC at ETH Zurich (Wellig and Moschytz 1999, Zennaro et al 2003) allow now the collection of thirty minutes and more of data in a controlled setting, which will allow to describe neuromotor control more and more precisely. Eventually the Cinderella hypothesis may be proven in observations during a whole work day.

2.3 Strain factors specific to keyboard and pointing devices

Early investigations have mostly been undertaken before the introduction of the computer mouse and other pointing devices. Only a small number of more recent studies focused on mice and even fewer on alternative devices such as trackballs, touchpads, joysticks or pens. Today however, mouse usage accounts for a large part of computer operation, and graphical user interfaces heavily relying on the mouse have greatly transformed the interaction with the computer. At the same time, prevalence of pain and discomfort increased. Its occurrence was found to be higher on the right body side (Woods et al, 2002). As mice are almost always placed on the right side of the keyboard, even by left-handers, this suggests a correlation between WRMD and the rising use of mice.

The mouse is typically used to open and close programmes and documents, to move windows, to mark, copy and paste text or objects, to scroll, and to access items in pull-down and toolbar menus or in menus appearing at a right button click. The mouse facilitated and accelerated computer work to a high degree and led to a certain standardisation of typical tasks in programmes like word processing, e-mail, web browsing, spreadsheet processing, accessing data bases, graphics, CAD, programming or accounting.

A key issue with mice are the prolonged static and constrained postures with excessive deviations of certain joints which accompany typical use. Excessive deviations from a neutral hand and arm position can result in strain and disorders if assumed for prolonged duration. A neutral position is a position that the body, or part of the body, assumes when completely relaxed. A deviation is considered excessive if exceeding 30% of the maximum possible range of deviation from neutral (Burgess-Limerick et al 1999). Table 1 gives examples for the wrist (ISO, 2000).

Table 1 Maximum range of deviation from neutral and excessive deviation in degrees for the wrist

	max. range of deviation from neutral (5th/95th percentile)		excessive deviation (30% of max. range) (5th/95th percentile)	
	female	**male**	**female**	**male**
wrist extension	57°/88°	47°/76°	17°/26°	14°/23°
wrist flexion	54°/90°	51°/85°	16°/27°	15°/26°
radial deviation	17°/37°	14°/30°	5°/11°	4°/9°
ulnar deviation	19°/37°	22°/40°	6°/11°	7°/12°

Keyboard and mouse operation can cause a variety of deviations. Disorders can arise from an unfavourable base posture (fingers placed on keyboard or hand placed on mouse), from manoeuvring a device (mouse moving), and from using the fingers to operate a device (typing, mouse clicking). The frequency and amount of deviations are sometimes used as an indicator of biomechanical stress. The following lists the main deviations that can be observed with traditional keyboards and mice, resulting from a combination of device design, individual workstation configuration and behaviour:

- *Shoulder elevation:* Too high a desk can lead to permanent light shoulder elevation of both arms with increased activity in the trapezius muscle (Zennaro et al 2004). Unsupported handballs during keyboard operation may also lead to shoulder elevation.

- *Shoulder rotation and arm abduction:* Standard keyboards are unsymmetrical and incorporate a numeric bloc on the right side, increasing the distance between the body midline and the mouse (placed to the right of the keyboard). This leads to an unsupported right arm, with permanent abduction and shoulder rotation (lever principle!) and possibly to unfavourable flexions of the spine. Females with typically narrower shoulders are affected more than males.

- *Forearm pronation:* Forearm pronation (rotation towards the centre of the body, i.e. counter-clockwise in the right arm) occurs with both hands in operating a traditional keyboard and with the right hand in operating a mouse. The hand is forced into a position more or less parallel to the desk.

- *Wrist ulnar deviation:* Ulnar deviation (lateral rotation of the hand in the direction of the little finger) is highly present in the traditional keyboard that forces the finger tips in line with the horizontal rows of keys. Ulnar deviation can also be seen in mouse operation, especially in horizontal movements towards the right from the actual position (e.g. when marking several words in a line of text).

- *Wrist extension:* Wrist extension (bending of the hand at the wrist away from the palm) occurs with keyboards, especially with a low desk, and with mice, depending on their height. A flat mouse will cause less extension. Additional extension can result when sliding the mouse towards the body without moving the arm.

- *Finger extension:* To avoid accidental keying, the fingers need to permanently 'float' above the keyboard, which is achieved by a combination of finger and wrist extension. The same happens with the fingers on top of the mouse. In double-clicking, the index finger needs to be lifted isolatedly, rapidly and with high force between the clicks, possibly causing excessive doublet rates (Sjøgaard et al 2001, Søgaard et al 2001).
- *Finger flexion:* Intermittent finger flexion occurs during any depressing of a key or mouse button. Though fingers have been 'designed' for flexing, the cumulation of thousands of flexions during a workday (secretaries may perform 100.000 keystrokes in a day) may exceed their capacity.
- *Finger abduction:* Permanent finger abduction (lateral separation of the fingers) occurs with the mouse, depending on its size and shape and the spacing of the mouse buttons, and with the keyboard in performing combinations like ctrl-s, ctrl-x, ctrl-c, ctrl-v with the pinkie and index finger of the same hand.

Another important issue with mice are *antagonistic co-contractions:* Due to the shape and size of mice, precise positioning can only to a certain extent be achieved with the finger muscles (the 'normal' muscles for fine motor skills); instead, part of the movement is carried out with the wrist, elbow or even the shoulder. In order to achieve the required precision, agonists and antagonists need to be contracted simultaneously and the fine movements are achieved by a modulation of the countermoving muscles. With clicking and especially double-clicking, the finger flexor and extensor muscles need to develop high forces, while the mouse must not be displaced until the end of the action. This stabilisation can be achieved by antagonistic co-contractions of high force. In a typical CAD designer this happens several thousand times each day.

Ergonomists have sought alternative input devices to overcome unfavourable postures and muscle activations. So-called *'ergonomic'* or *'natural'* keyboards, e.g., can turn the forearms into a more neutral position. Pronation and ulnar deviation may be reduced to some extent. But their usually broad and bulky design implicates a mouse placement even further to the right than with a standard keyboard. *Wrist supports* and a *desk* that is not too low can reduce wrist extension. Too high a desk on the other side increases shoulder activity (Zennaro 2004). L-shaped desks with the screen positioned in the deep apex of the desk can support the right or both arms and reduce pressure to the wrists and forearms. But even a properly adjusted desk height might be futile and bring up lateral flexions of the spine if the mouse is placed too far from the body midline.

A keyboard with a *numeric bloc* on the *left* instead the right side, or with a separate or detachable numeric bloc, could bring the right arm to a more centred position and alleviate shoulder strain. A side-effect of a this would be a more comfortable entry of numeric data, with the left hand entering the data and the right hand operating the mouse instead of alternating the right hand between numeric bloc and mouse. *Touchpads* on laptops and *track-point mice* (a small joystick placed in the centre of the keyboard) should also reduce arm abduction (Fernström and Ericson 1997). Touchpads might reduce wrist extension but not finger extension. In keyboards, finger extension might be countered with higher *key touch forces* and longer *key travel* (not what is usually found in laptops).

A *curved mouse*, moulded to the right hand, or a *curved trackball* with a built-in rest for the right hand should reduce pronation to some extent. Burgess-Limerick et al (1999) found reduced ulnar deviation with a trackball, but increased wrist extension. *Joysticks* can reduce wrist extension, finger extension, finger abduction, ulnar deviation and pronation (Aarås 1997), but might move the forearm into unfavourable supination. Aarås compared a joystick mouse with a traditional mouse and found reduced muscle load on the forearm with the joystick. Joysticks however require a ‘power’ rather than a ‘precision’ grip which may have precision and performance implications (Woods et al 2002) and lead to antagonistic co-contractions. A *light-operated* instead of a mechanical mouse facilitates movement and increases precision. If it can be used without a mouse mat, it offers the option to be quickly repositioned to different places on the desk, or to temporarily be used by the non-dominant hand.

A so-called *pen*, an alternative pointing device operated on a tablet, leaves the arm, hand and fingers in a rather neutral posture; pronation, ulnar deviation, wrist extension, finger extension and finger abduction should be reduced. It is operated with the fine motor muscles of the fingers. Ichikawa et al (1999) investigated two pen/tablet devices with regard to performance, accuracy, mental workload and subjective ease of operation, and compared them to the mouse. They found shorter pointing time and higher accuracy in the pen, but subjectively, the mouse was favoured for ease of pointing and load to the wrist, elbow, arm and shoulder. The pen will be subject to a study in experiment 3 of this thesis.

2.4 PROCID

Recognising the relevance of WRMD when working with computers, an international group of researchers launched the project PROCID, which stands for *Prevention of Muscle Disorders in Operation of Computer Input Devices.* The project, funded as a concerted action under the European Commission research programme BIOMED-2 (Biomedicine and Health Research) conjoined from 1998 until 2001 a multidisciplinary consortium with ten research groups from Sweden, Denmark, Italy and Switzerland. The Institute of Hygiene and Applied Physiology (IHA) at the ETH Zurich was one of the partners, and the experiments in this thesis were mostly planned and realised within PROCID.

The approach pursued in PROCID focussed mainly on the mentioned Cinderella hypothesis, claiming that a small number of muscle fibres may constantly be active in certain muscles of persons working at computers, become metabolically overloaded and degenerate. The project aimed at developing a knowledge base with respect to basic physiologic phenomena involved, developing a methodology for recording and analysis of intramuscular EMG signals from exposed muscles, and carrying out studies under specific, provocative situations. The single research objectives were:

1. Development of intramuscular measurement techniques suitable for mapping MU recruitment during operation of computer input devices.
2. Development and evaluation of signal processing algorithms for identification of single MU potentials under dynamic conditions.
3. Evaluation of MU recruitment in dynamic tasks, in normal subjects and in patients with pain syndromes.
4. Experimental evaluation of muscular strain at the MU level, in operation of different classes of computer input devices.
5. Experimental evaluation of stress induced muscular tension at the MU level, in computer operation.
6. Mapping of MU firing patterns in sustained working situations.

The objectives were included in a series of 13 synchronised work packages with the IHA contributing experiments on motor-unit behaviour in one-sided and repetitive tasks. The concerted action included two symposia (Copenhagen 1999 and Gothenburg 2001) and ended with a final report formulating recommendations for design and work with computer input devices (see concluding discussion).

3 Objectives

Work related musculoskeletal disorders (WRMD) in human-computer interaction (HCI) affect the entire upper extremity including fingers, wrists, arms, shoulders and neck and may also spread to the head, eyes, lower back and other areas. The objective was to investigate a series of these muscles in respect to unfavourable motor activation patterns when performing typical, or abstract, actions with the fingers such as tapping, typing or clicking. The muscles were, first of all, investigated in respect to unnecessary co-activity. It is assumed that co-activity, unvarying stabilising activity (resulting from constrained postures) and antagonistic activity are all main causative factors for WRMD in HCI.

In the terminology here, the word 'co-activity' is used for activity of muscles not primarily involved in the task (such as typing or operating a mouse), presumably as a result from a restricted differentiation of neuromotor control, and discriminates this from simultaneous antagonistic activity (often termed 'co-contraction') of the effector muscles (the finger extensors/flexors in this case). Antagonistic co-contraction was not the topic of this study. Stabilising activity is diverse from co-activity, though it will sometimes be included in the meaning, when it is closely correlated with the task performed but not unconditionally needed from a functional point of view. However the line between activity, co-activity and stabilising activity is, at times, problematic. The shoulder, e.g., can stabilise the arm, help operate the mouse, or be co-activated without any functional relevance.

After having identified typical co-activity patterns with a finger tapping task, and realising that the observed activity levels were too low to be the cause for chronic and degenerative pain, it was hypothesised that motor control might fail and that some motor units might be recruited during extended periods, despite being metabolically exhausted. Such behaviour has been described by Hägg in 1991 with the Cinderella hypothesis (see 2.2), based on the presumption that the force demand is low, compared to the muscle's capacity, but ongoing. The aim was thus to find if co-activity of the trapezius muscle is linked to Cinderella (or other distinctive motor unit) behaviour. It was hypothesised that n*eck pain may be initiated by the ongoing use of input devices causing trapezius muscle co-activity during extended periods. Since the co-activity levels are low, the motor unit recruitment control may fail as described by Hägg's Cinderella hypothesis (1991). Such failure would lead to cell damage and pain.*

If a dependence of co-activity and hazardous MU patterns on input devices, task characteristics and behaviour can be shown, the results could contribute to the ergonomic improvement of devices, workstations and software and to recommendations concerning personal behaviour or intervention strategies.

The assumptions were to be investigated in controlled experimental settings with healthy (i.e., not currently suffering from WRMD (work related musculoskeletal disorders)), right-handed subjects.

4 Physiological Basics

The experiments contained in this thesis were conducted on the muscles in the chain neck-arm-fingers, i.e. the trapezius, triceps brachii, biceps brachii, extensor digitorum communis and flexor digitorum superficialis. Skeletal muscles are built up from muscle fibres which can be either of the slow-twitch type (type I), contracting slowly and fatiguing late, or the fast-twitch type (type II), contracting fast and exhausting quickly. Control complexity is reduced by the muscle fibres organised in groups called motor units (MUs). A MU is controlled as a whole, i.e. by action potentials ('firings') transmitted by a single α motor neuron. The tension of a muscle is modulated by the firing rate on one side, and the number and size of recruited MUs on the other side. Motor control happens at different levels from involuntary simple spinal reflexes to consciously initiated complex patterns involving different muscle groups. The standard method to measure muscle activity is electromyography (EMG). Surface EMG uses electrodes attached to the skin and measures the summed electrical potentials of many MUs, while intramuscular EMG is recorded by needle or wire electrodes inserted into the muscle, detecting activity only from nearby MUs. With the aid of a decomposition programme this data can be used to log the exact firing train of each recorded MU.

4.1 Anatomy of the investigated muscles

The trapezius muscle is a flat, triangular muscle that covers the upper and back part of the neck and shoulders, originating at the base of the skull and the spinous processi of the 7th cervical and all of the thoracic vertebrae and attaching down in the middle to lower back (Figure 1). Together with the rhomboideus major, rhomboideus minor, levator scapulae and latissimus dorsi the trapezius connects the upper extremity to the vertebral column. The two trapezius muscles together resemble a trapezium, or diamond-shaped quadrangle. The superior fibres proceed downward and lateralward into the clavicle, the inferior upward and lateralward, converging near the scapula, and the middle horizontally, attaching at the acromion and the spine of the scapula. When the whole trapezius is in action it retracts the scapula and braces back the shoulder; if the head is fixed, the upper part of the muscle will elevate the point of the shoulder, as in supporting weights; when the lower fibres contract they assist in depressing the scapula. The middle and lower fibres of the muscle rotate the scapula, causing elevation of the acromion. If the shoulders are fixed, the trapezii, acting together, will draw the head directly backward, or if only one acts, the head is drawn to the corresponding side.

The biceps brachii (or just biceps) is a long, two-headed muscle, placed on the front of the upper arm. Its main role is to flex the elbow. The three-headed triceps brachii (or triceps) is situated on the back of the upper arm, extending the entire length of the dorsal surface of the humerus. The triceps stretches the elbow and is the direct antagonist of the biceps. A number of muscles is situated in the forearm, controlling the movement of the fingers and the hand in all directions in a complex way. Two of the main forearm muscles were investigated: the extensor digitorum communis (Figure 2, left) and the flexor digitorum superficialis (or sublimis) (Figure 2, right).

4.2 Structure and physiology of skeletal muscle

4.2.1 The muscle fibre

Muscles are the contractile tissues of the body. They are built from muscle fibres, elongated cells that contain many nuclei evolving from fusions of single-nucleus cells, so-called myotubes, in the embryonal stage. Muscle fibres or myofibrils range from 10 to 100 μm in diameter and from 0.5 to 12 cm or more in length. Morphologically, muscles can be described as striated or smooth, depending on the degree of organisation of the contractile filaments. Striated muscles include cardiac and skeletal muscles. The skeletal muscles are not uniform; some are pale in colour while others are more red. The redness reflects the amount of myoglobin in the muscle fibre. Myoglobin is the specialised haemoglobin-containing oxygen-storage protein of striated muscle. A high myoglobin content endows the fibre with a high capacity for aerobic metabolism. The fibres with the highest myoglobin content have a relatively slow rate of shortening; these reddish, slow-twitch fibres are categorised as type I fibres. They contract slowly, but are resistant to fatigue and primarily used for postural control. Most fast-twitch fibres have a low myoglobin content and are dependent on anaerobic metabolism (type IIb), while some have moderate myoglobin levels and aerobic capacity (type IIa). Type II fibres contract fast, are quickly exhausted and primarily used for ballistic tasks. All skeletal muscles in the human body contain a mixture of type I and type II fibres, in the combination needed for the specific skill. The fibres of one motor unit (see below) however are all of similar type. At birth, the fibres aren't differentiated; the separation happens during usage of the muscle and can therefore be influenced by individual behaviour or workout.

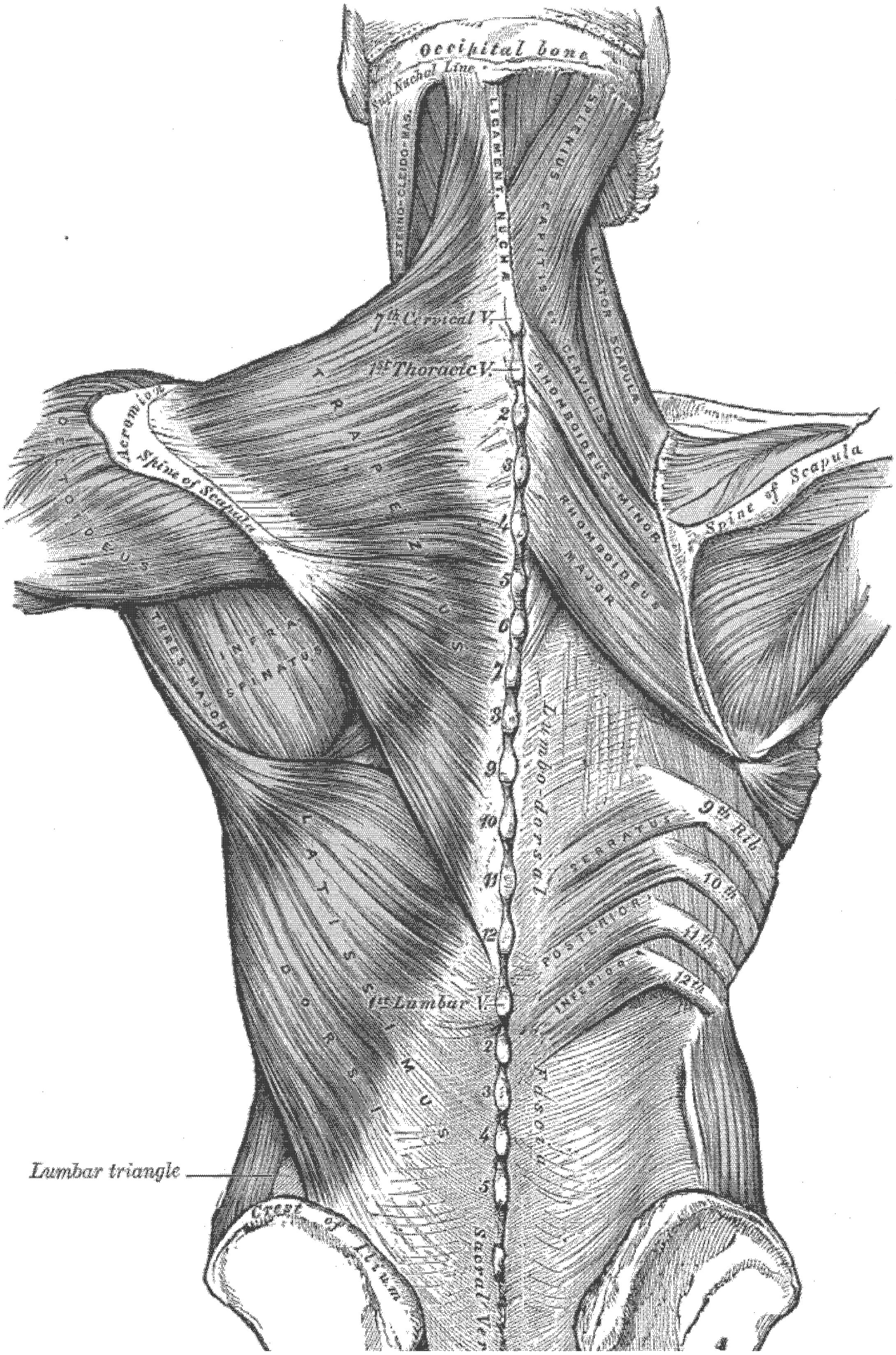

Figure 1 The muscles of the back
(from: http://education.yahoo.com/reference/gray/subjects)

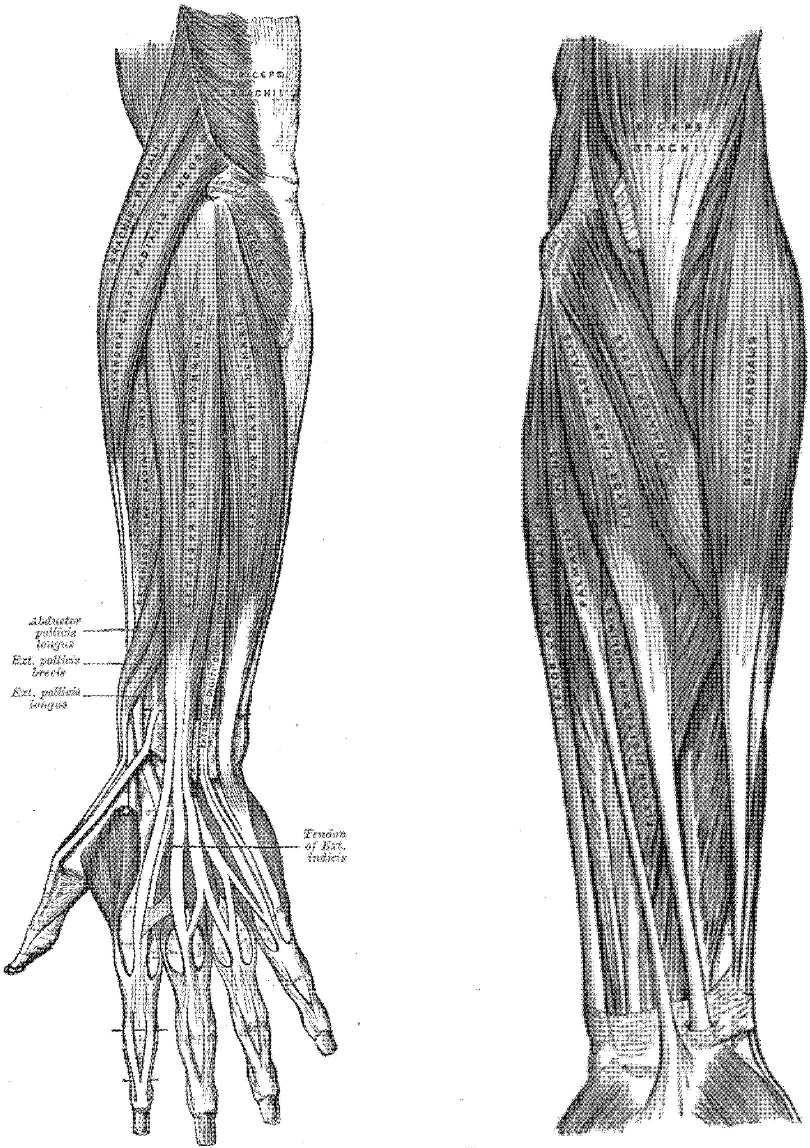

Figure 2 The muscles of the forearm. Left: extensor muscles; right: flexor muscles (from: http://education.yahoo.com/reference/gray/subjects)

Most muscle fibres do not span the whole length of the intact muscle. At one end of the muscle, the fibres extend from the tendon and end in long tapering points that interdigitate with other fibres. The fibres are tightly bound together by intrafascicular connective tissue, the endomysium (Figure 3). Several lengths of bound muscle fibres are often required before the final fibres reach the tendon at the other end of the muscle. Functionally, however, muscles behave as if they were groups of fibres extending from tendon to tendon, passing across one or more joints.

The integrity of individual skeletal muscles is maintained by a framework of connective tissue: that enclosing the whole muscle is termed the epimysium. Smaller and smaller bundles of muscle fibres are enclosed by sleeves of connective tissue, the perimysium, that are protrusions of the epimysium into the body of the muscle. The smallest bundles visible to the naked eye are termed muscle fascicles; these are made up of 12 or more fibres enclosed by their perimysium. In addition to holding the individual fibres together, the endomysium also provides the architecture to hold capillaries and nerves in place.

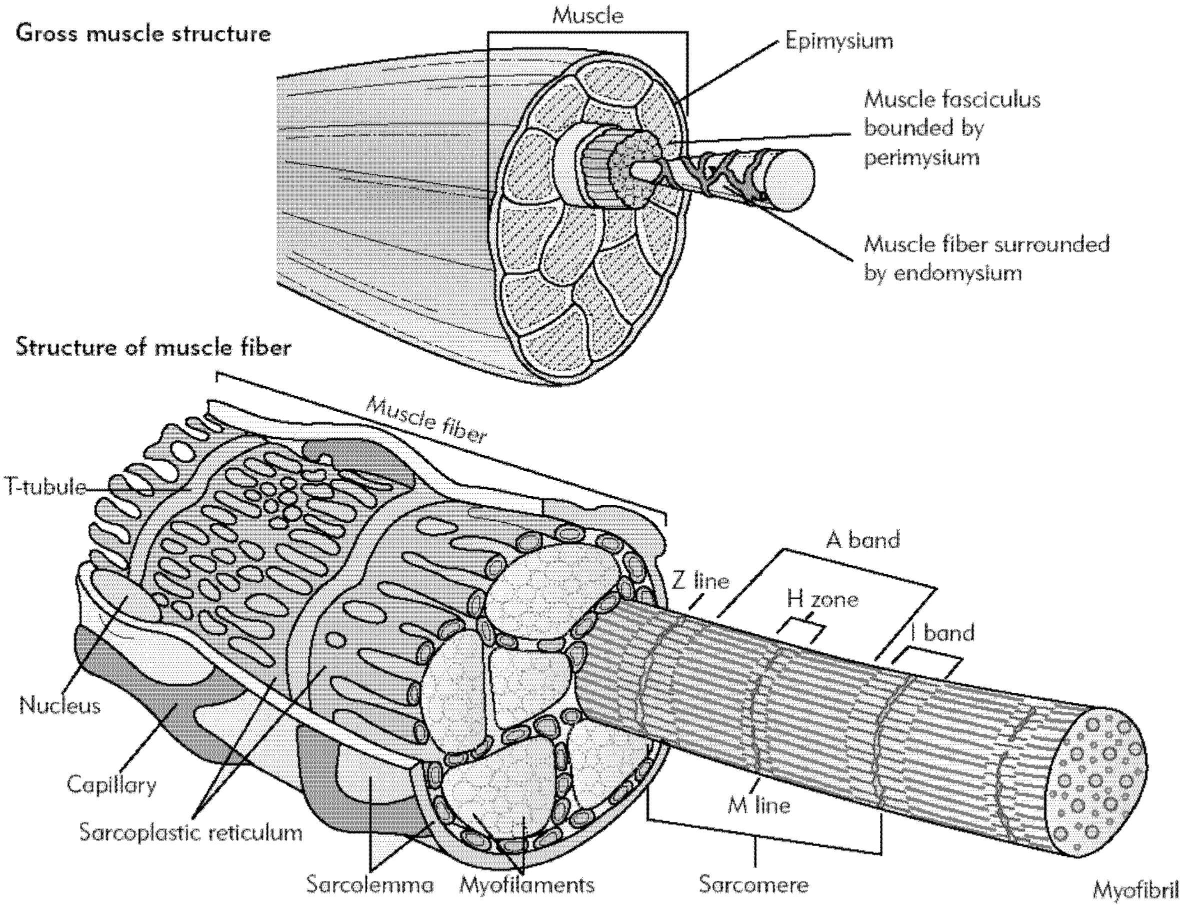

Figure 3 The structure of skeletal muscle (Marieb 2003)

Movement of the skeleton is achieved by shortening, or contraction, of muscles. Each muscle fibre contains thousands of contractile units, myofibrils, made up of sarcomeres arranged in series in the long axis of the fibre. The myofibrils contain filaments of two types, thin and thick, which are arranged to form the lines and bands that are visible microscopically. The thin myofilaments consist of three major types of protein: actin, tropomyosin, and troponin. The thick myofilaments are formed from bundles of myosin, which consists of helical chains and a double globular head. There are several isoforms of myosin, which determine the twitch speed of the fibre.

The characteristic of myosin and actin is that they can shift in relation to each other when energy is supplied. Shortening of the sarcomere is achieved by the drawing together of opposing thin filaments by a ratchet-like effect of the thick filaments. The actin filament has a series of myosin-binding sites that sequentially bind with increasing affinity to the head processes of the myosin molecule. The contractile process is dependent on the presence of Ca^{2+}. The major internal store of Ca^{2+} in skeletal muscle is the sarcoplasmic reticulum. ATP is essential for both muscle contraction and relaxation as the immediate source of energy.

A muscle fibre can only be in one of two contraction states; it is either relaxed or fully contracted. In the contracted state its length is reduced to about 57% of its resting length. Contraction and release usually occur in a fast interplay that appears to be random. Together with the activation of the muscle's antagonist this allows acceleration and position control of the limb. Muscles can only pull and not push; this is why a muscle needs always to collaborate with at least one antagonist. As most muscles run over more than one joint, the central nervous system must control a specific movement by an accurate activation of a number of synergists and antagonists.

4.2.2 The action potential

The nervous system has to control and co-ordinate the activities of the single organs and the reactions of the body on outside changes. This is achieved by changing the electric potential (voltage) of nerve cells by means of Na^+ and K^+ ions, conducted as action potentials over extended distances. A nerve cell (neuron) consists of a cell body (soma), a number of dendrites gathering the excitations from other neurons, and an axon, which can be very long and transmits the neural excitation of the soma chemically to other neurons (dendrites) via synapses (synaptic gaps) or to a muscle fibre via a motor end plate by rapid secretion of neurotransmitter molecules. The excitation of a cell (stimulation or suppression of an action potential) depends on the sum of signals from all dendrites and the neurotransmitters and receptors at their synapses. Signals are sent in a series of pulses of action potentials. Stronger signals, corresponding to larger stimuli, are sent with a higher frequency of pulses, rather than larger pulses.

The total duration of an action potential is in the order of magnitude of 1 ms in a neuron (Figure 4) and several milliseconds in a muscle cell (striated muscle). Neural and muscle cells have a nominal rest potential of about -80... -70 mV. An action potential manifests as a rise to about +30 mV ('depolarisation'), followed by a return to the rest potential ('repolarisation'). In muscle cells, the repolarisation is slower than in neurons and may take about 10 ms (200 ms in the heart muscle). In neurons (but not in muscle cells) the repolarisation typically overshoots the rest potential to about -90 mV. This is called hyperpolarisation and would seem to be counterproductive, but it is actually important in the transmission of information. Hyperpolarisation prevents the neuron from receiving another stimulus during this time, or at least raises the threshold for any new stimulus. Part of the importance of hyperpolarisation is in preventing any stimulus already sent up an axon from triggering another action potential in the opposite direction. In other words, hyperpolarisation assures that the signal is proceeding in one direction.

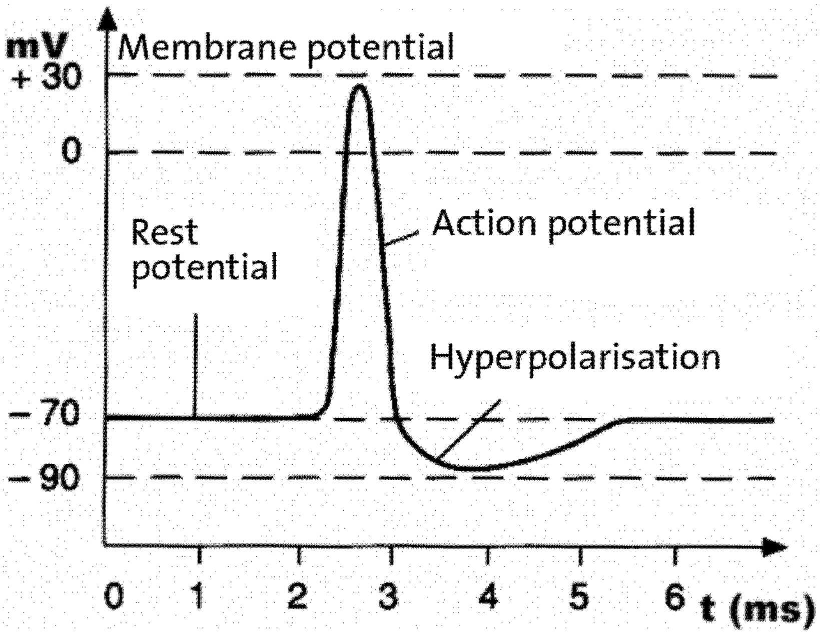

Figure 4 Action potential of a neuron

4.2.3 The motor unit and the regulation of the force of muscle contraction

The control of each individual muscle fibre would be much too complex for the central nervous system. This is why muscle fibres are organised in motor units (MUs), the smallest functional unit. Depending on the precision a muscle must achieve, MUs contain from less than ten up to hundreds or even thousands of fibres (for fine or gross motor skills, respectively). A muscle contains between about five and one thousand MUs. The fibres of the different MUs of a muscle are intermingled and spread over a section of about 5 to 10 mm where they are usually mixed with fibres from another 5 to 30 MUs (Figure 5).

A MU comprises an α motor neuron, the muscle fibres that it innervates, and the neuromuscular junctions that form the chemical synapse between the neuron and the muscle fibre. Each α motor neuron branches at its terminus and supplies all fibres of the MU. Stimulation of a muscle fibre follows the transduction of an action potential arriving at the terminal swelling of a motor neuron into an action potential at the post-junctional region of the neuromuscular junction, the motor end plate. This occurs through the release of acetylcholine. An action potential generated at the motor end plate spreads across the sarcolemma and down the invaginations of this membrane, the T-tubules.

If a second stimulus is within 8 milliseconds of the first, the plasmalemma will be electrically refractory and no second response will be seen (Figure 7). However, following the first stimulus, myoplasmic Ca^{2+} remains elevated for approximately 50 milliseconds and tension does not return to the prestimulation level for a further 30 milliseconds (Figure 6). Therefore, a second stimulus applied 8–80 milliseconds after the first will have an additive effect, known as summation. Multiple stimuli at stimulation intervals of 40–80 milliseconds will produce stepwise increases in tension, known as steppe. At stimulation intervals of less than 40 milliseconds, the steppes become fused to give a tetanic response.

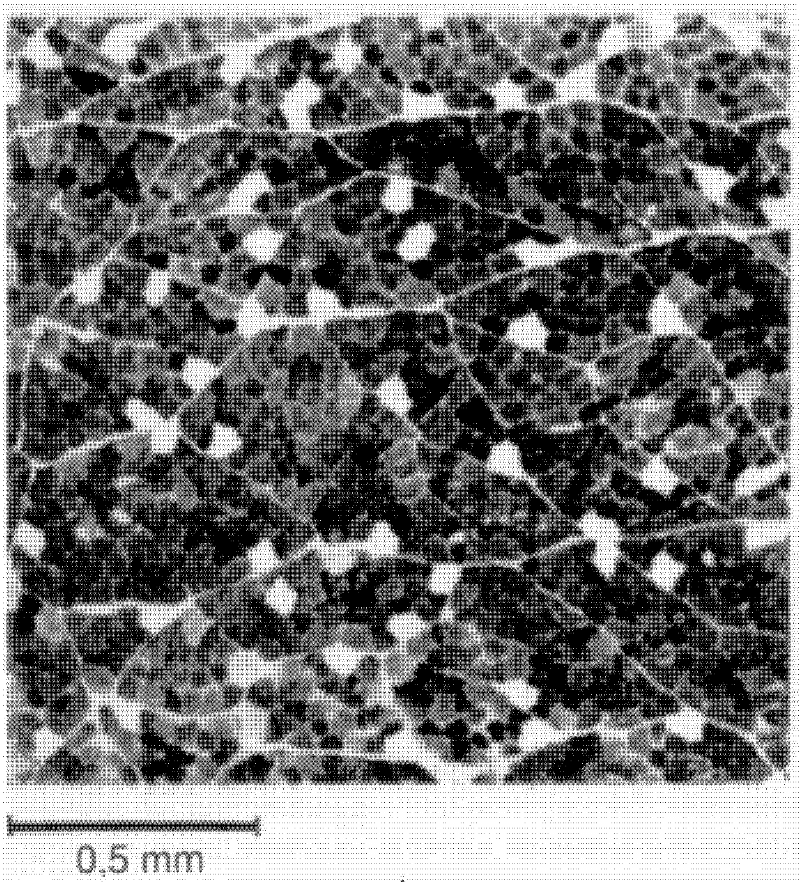

Figure 5 Motor unit (MU) distribution: The white fibres of this muscle cross-section belong to the same MU. A MU contains from a few up to several hundreds of muscle fibres. It shares a territory of about 5-10 mm with 5-30 other MUs

All muscle fibres of a MU are innervated by a common motor nerve and will, therefore, contract simultaneously. Not all MUs in the same muscle will, however, contract at the same time. If a muscle at rest is required to increase its tension gradually, the smallest MUs will be activated first, with successively larger MUs being recruited as greater force is required. Thus summation of responses at the single fibre level and recruitment at the MU level combine to enable a continuum of tension development over a wide range.

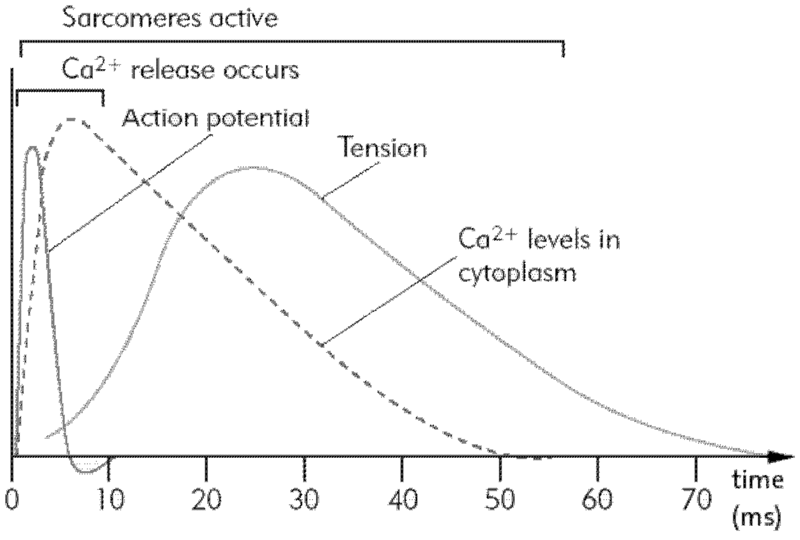

Figure 6 Timing of events in muscle fibre contraction: action potential, release of Ca^{2+}, and tension generated (after Marieb 2003)

4.2.4 The motor unit action potential (MUAP)

When the motor end plate of a muscle fibre is depolarised, the depolarisation propagates in both directions along the fibre. This generates an electromagnetic field in the vicinity of the fibres that can be detected by an electrode. A schematic representation of this with n parallel muscle fibres of one MU is shown in Figure 8. Depending on the location of the end plate on the muscle fibre in relation to the (bipolar) electrode (muscle fibre conduction velocity is 3 to 6 m/s), and to some extent on the length of the nerve branch leading to the end plate (nerve conduction velocity 50 to 90 m/s), the electrode sees the action potential propagating on each fibre with a certain time delay as represented on the right of the figure. Also, as the electrode pair has a positive and a negative part, it will see the single action potentials starting either with a positive or a negative phase, depending if the motor end plate is situated left or right of the electrode. Finally, the distance between fibre and detection site affects the signal amplitude, and the tissue will work as a filter. The spatial-temporal superposition of all action potentials from one MU, as seen by the electrode, is a multiphasic signal. It is called a motor unit action potential (MUAP). A MUAP as seen by one electrode is unique, which is the base for decomposition programmes to distinguish the firings originating from different MUs, all seen at the same detection site. Peak-to-peak MUAP voltages detected by a bipolar intramuscular electrode range from a few µV to 5 mV with a typical value of 500 µV. The phases of MUAPs may range from one to four with the following distribution: 3% monophasic, 49% biphasic, 37% triphasic and 11% quadriphasic. A MUAP duration may range from 1 to 13 ms.

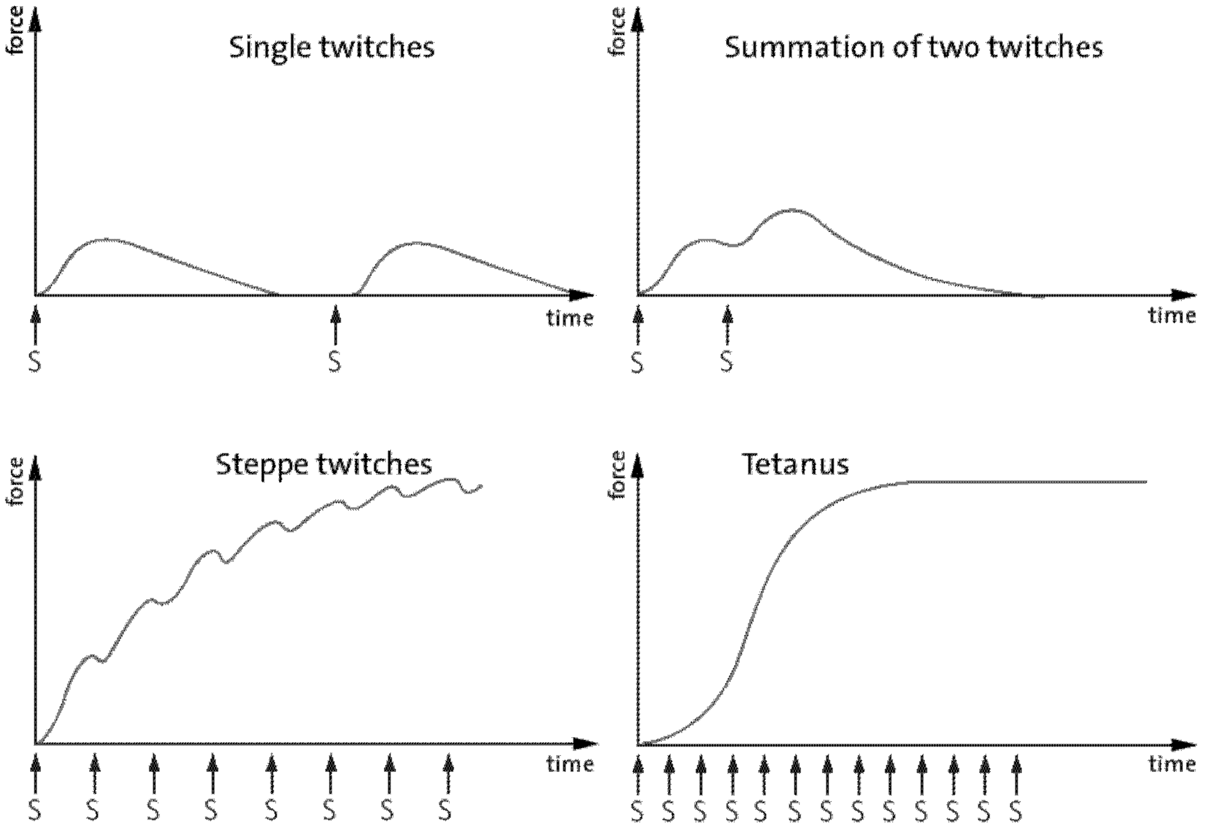

Figure 7 The effect of stimulus interval on the force of contraction: single twitches; summation of two twitches; steppe twitches; and tetanus (after Marieb 2003)

4.3 Spinal motor control

Control of skeletal muscle contraction is achieved at several levels, ranging from involuntary simple reflex responses to consciously initiated complex patterns involving many different muscle groups. In order to carry out a particular manoeuvre, the effectors (agonists) of the response need to be activated and, in addition, the muscles having the opposite effect (antagonists) need to be inhibited. In many movements, compensatory responses are required: for example, to maintain posture and/or balance. As with any control system, feedback information is required if useful output is to be achieved. In the context of control of muscle contraction and movement of the skeleton, this feedback or sensory information is known as kinaesthesia. Body position sense is a function of the proprioceptive receptors located in the joints, but there are also mechanisms for sensing the tension, length, and rate of shortening of the skeletal muscles. The receptors for detecting muscle tension are located in the tendons and are called the Golgi tendon organs. Afferent signals from the Golgi tendon organs are relayed up the spinal cord to higher centres but also synapse at the spinal cord level to inhibit the efferent supply to the muscle via its α motor neurons. The receptors for muscle length and change in length are found in the muscle spindle complexes.

The spinal reflexes and automatisms represent a stock of elementary posture and movement blocks that are highly controllable and adjustable by higher instances of the CNS to the specific context. The organism can make use of them without the higher instances needing to bother about the details of execution.

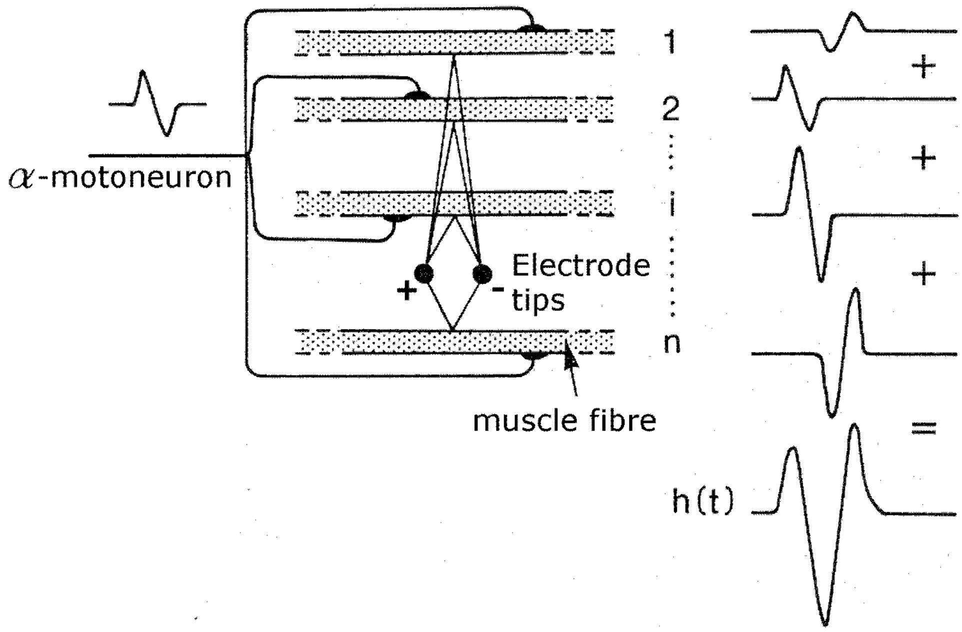

Figure 8 Schematic representation of the generation of a motor unit action potential (MUAP) (Basmaijan and de Luca, 1985)

4.3.1 Muscle spindles and the reflex system of the Ia afferents

Muscle spindles are encapsulated adapted muscle fibres of up to 12mm in length orientated so that the enclosed intrafusal fibres are arranged parallel to the force-generating, or extrafusal, fibres. They function as sensors for muscle length. Apart from several intrafusal fibres (so-called nuclear-bag and nuclear-chain fibres) they contain sensory axons and γ motor neurons[1]. The intrafusal fibres detect changes in length, the sensory axons (on the equatorial region) relay the information to the CNS, and the γ motor neurons (contractile structures on the peripheral region) adjust the sensitivity of the sensors. Two types of sensors, the primary (Ia) and the secondary

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[1] γ motor neurons are small neurons innervating the intrafusal fibres ('fusimotor system'); α motor neurons are larger neurons innervating the extrafusal fibres ('skeletomotor system')

(II) muscle spindle afferents, provide a proportional-differential input, i.e. they register static (II-fibres) as well as dynamic (Ia-fibres) changes.

Muscle spindles are located throughout the body of muscles, being more numerous in muscles with higher proportions of small MUs. The structure of the muscle spindle and its innervation is illustrated in Figure 9, its role in muscle control in Figure 10.

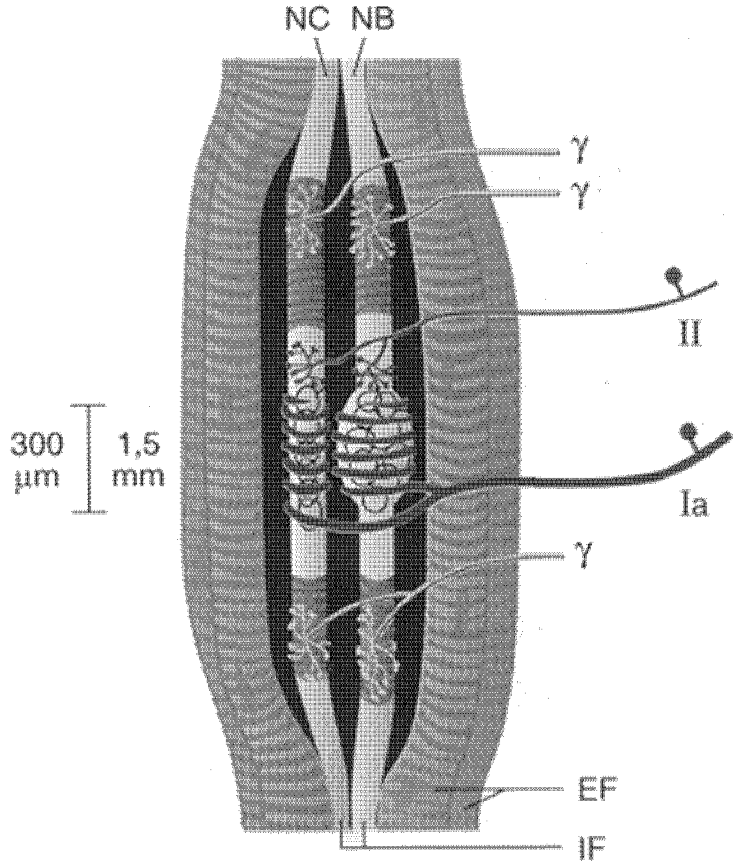


Figure 9 Muscle spindle. EF: extrafusal fibres; IF: intrafusal fibres; NB: nuclear bag fibres (each spindle contains 2 NB fibres; only one shown); NC: nuclear chain fibres (up to 10 in each spindle); Ia and II: afferent sensory fibres; γ: γ motor neurons with motor end plates on contractile structures of the intrafusal fibres. The left scale applies to the equatorial regions, the right scale to the total muscle spindle (Schmidt 1995).

The spindle afferent fibres enter the spinal cord through the dorsal root and branch to make connections at their segmental level of innervation and to pass up the dorsal columns to higher centres. Via the γ motor neurons the CNS influences the spindles directly: Their activation results in a shortening of the intrafusal fibres, causing a change of sensibility of the sensors. The fibre shortening prevents furthermore that the sensors are folded up during a muscle contraction. This is why in CNS-controlled movements γ and α motor neurons are always activated jointly (α-γ-co-activation).

This allows a closed-loop-control: If the muscle has not yet reached the desired position (length) due to an external force, extrafusal and intrafusal fibres have different lengths. Via Ia-afferents this difference is projected to the homo- and heteronym motor neurons and summed up with the descending signal. This way the force can be adapted by recruiting additional MUs (load compensation reflex).

Another important loop is the stretch reflex for length stabilisation, raising up e.g. the body against gravity. A stretch of the muscle is projected monosynaptically by afferent Ia-fibres from the muscle spindles onto α motor neurons, causing a contraction reflex of the muscle. At the same time the Ia-fibres project to motor neurons of synergistic muscles and, via inhibitory interneurons, to antagonistic muscles, causing those to relax. The secondary muscle spindle afferents (II-fibres) are linked, by excitatory or inhibitory polysynaptic pathways, to virtually all motor nuclei of the extremity.

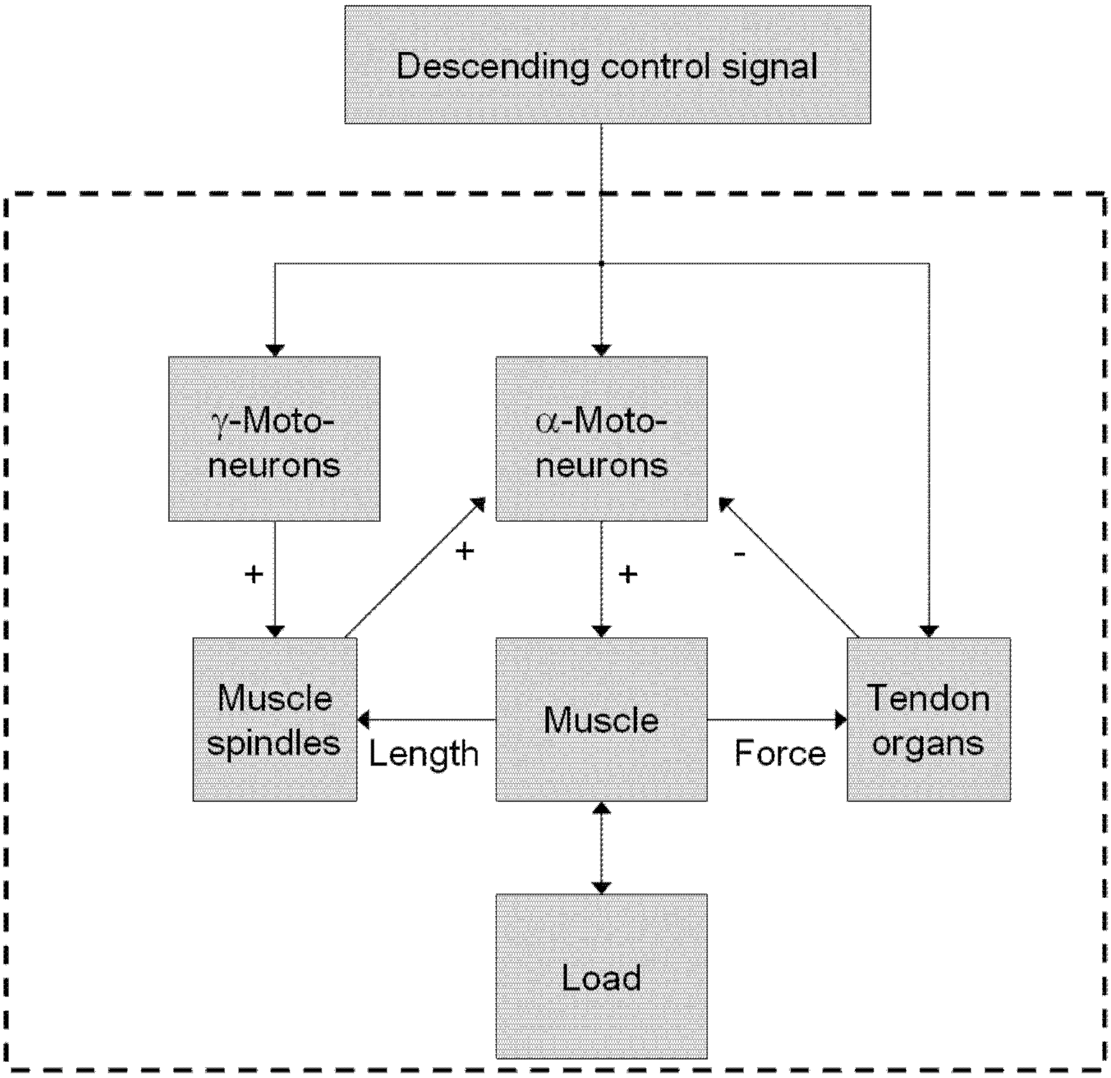


Figure 10 Muscle control by muscle spindles and tendon organs (synergistic and antagonistic muscles disregarded)

4.3.2 Golgi tendon organs and the reflex system of the Ib afferents

While muscle spindles are arranged parallel to muscle fibres, the Golgi tendon organs (or just 'tendon organs') are located in series between the muscle fibres and the tendon. They sense force (not length) and are so sensible that they can already be activated by the contraction of one single MU. Their behaviour is mainly proportional, although there exists a differential component. The registered force is projected polysynaptically to the α motor neurons by group I afferents, the Ib fibres. In contrast to the Ia afferents their action is inhibitory on the muscle (and its synergists), and excitatory on the antagonistic musculature. Additionally, the Ib afferents project to motor neurons of muscles of different joints of the same extremity. The degrees of excitation and inhibition is variable and depends to a great extent on the movement context. They are efficiently controlled by the descending pyramidal pathways.

4.3.3 The motor response to nociceptive stimulation

A noxious stimulus applied to a limb results in withdrawal of the limb from the stimulus. This is another spinally mediated reflex response. In fact, two reflexes are implicated: the withdrawal reflex affecting the injured limb and the crossed-extensor reflex affecting the contralateral limb. Nociceptive cutaneous afferents enter the dorsal horns of the spinal cord and send projections to interneurons in the cord. These interneurons are excitatory to the motor neurons supplying the flexors of the limb and inhibitory to the motor neurons supplying the extensors, resulting in flexion of the limb away from the stimulus. The nociceptive sensory afferents also have projections that cross to the contralateral side of the spinal cord before synapsing on interneurons. Stimulation of these interneurons leads to inhibition of the limb flexors and excitation of the extensors. The result of this crossed-extensor response is that the contralateral limb is made more rigid so that posture can be maintained during withdrawal of the stimulated limb. Other compensatory responses may also be activated: for example, movements of the other two limbs to help maintain posture and balance.

4.4 Supraspinal motor control

Simple motor tasks are controlled by spinal systems as described above. But the more complex and less automated the tasks get, the more higher areas of the brain are involved. These areas are organised in a hierarchical way that can be understood as an evolutionary adaptation of motorics to more and more complex tasks. Apparently, such adaptation was not primarily achieved by the transformation of existing motor systems but by superimposing new, effective structures. But at the same time, certain motor areas accomplished high specialisation, so that teamwork collaboration evolved alongside the hierarchical structures.

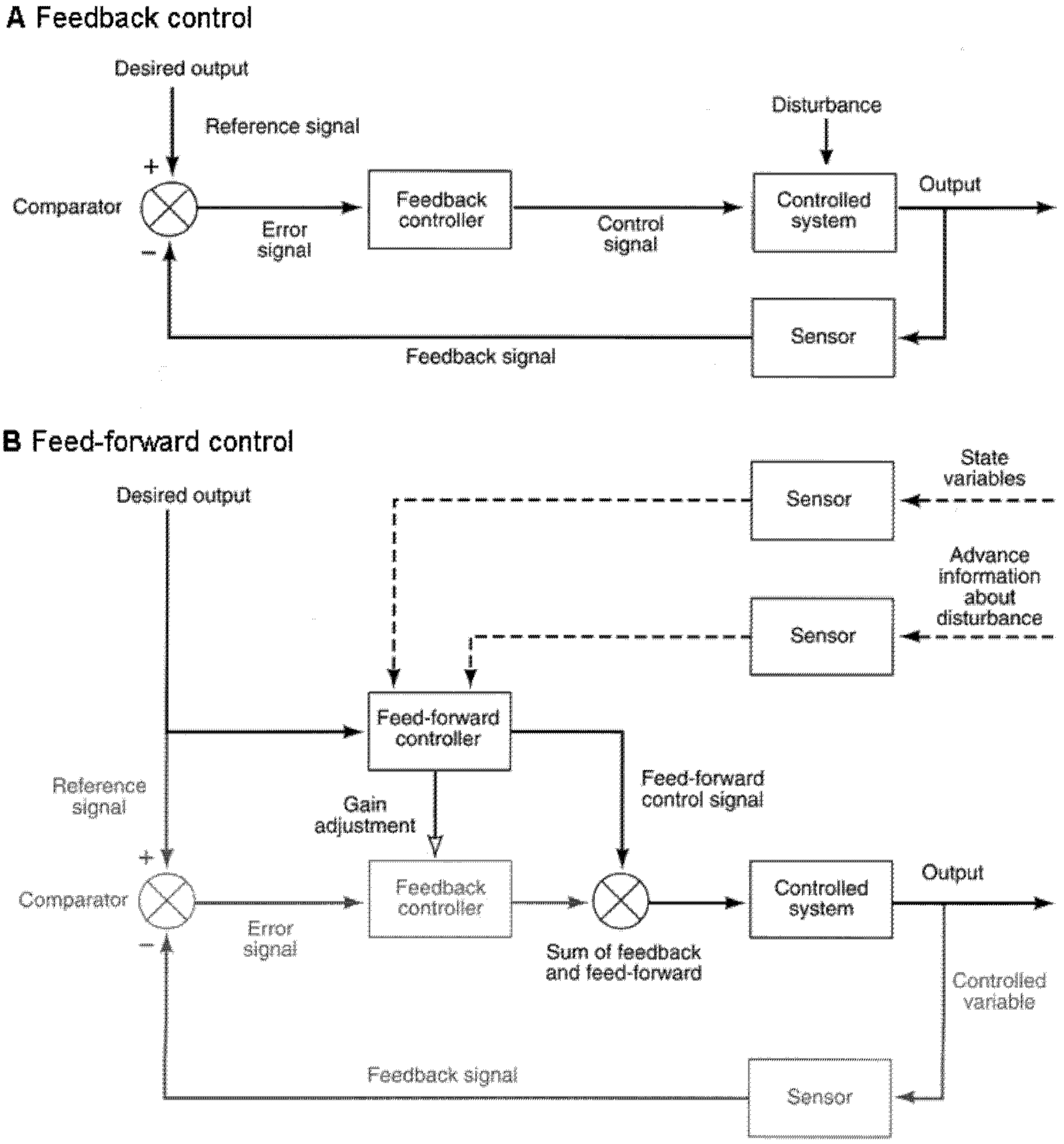
Although the skeletal muscles are under voluntary control, most muscle activity is carried out at a subconscious level. The cortical function is to activate motor programmes that have been learned and from previous experience will result in the desired outcome. A motor programme is defined as a set of commands that is generated in one area of the CNS before the onset of the relevant movement and that causes activation or inhibition of MUs in an appropriately timed sequence. Motor programmes can be generated at all levels of the CNS.

All senso-motor functions can be roughly classified in five elementary systems as shown in Table 2 with increasing levels of consciousness and control. Systems 1 and 2 comprise the monosynaptic and polysynaptic reflex arcs of the spinal cord with autonomous actions (system 1) and only to a small extent controllable movements (system 2). The vestibular nuclei (system 3) are specifically implicated in enhancing the tone of the postural muscles and coordinate actions to maintain posture against the influence of gravity (equilibrium). They are also involved in the temporal coordination of movements. The brain stem and extrapyramidal cortical areas govern involuntary, spontaneous and affective movements, posture control and learned movements of system 4. The most controllable, voluntary motor actions originate from the cortex (system 5).

Table 2 Functional classification of senso-motor systems (Rohen 1985)

	Type of action	**Controlled by**	**Functional system**	**Involved receptors for afferences**	**Degree of consciousness**
1	Simple myostatic control, muscle tone	Spinal cord (one segment)	Monosynaptic reflexes (esp. extension)	Muscle receptors (muscle spindles and tendon organs)	Automatic, unconscious
2	Primitive/rhythmic locomotion, isolated directed movements, escape reactions	Spinal cord (several segments)	Polysynaptic reflexes (esp. flexion)	Muscle receptors, skin receptors	Increasingly conscious
3	Equilibrium and muscle tone control, temporal coordination	rhombencephalon	Vestibular system	Equilibrium, muscle and skin receptors	Increasingly conscious
4	Learned and affective movements, posture control	Brain stem	Extrapyramidal system	All sensory organs	Increasingly conscious
5	Intentious and high-skill movements	Cortex	Pyramidal system	All sensory organs	Conscious, intentious

Sensory information is used to correct errors through feedback and feed-forward mechanisms. In a feedback system (Figure 11 A) a feedback signal is compared to a reference signal by a comparator. In reaching slowly for an object, the arm is the controlled system and the intended position of the arm is the reference. The difference between the position of the hand and the reference should be brought to zero to execute the action properly. If the hand is unexpectedly disturbed, an error signal is sent to the controller and a command to continue in the direction of the target is issued. Error signals are sent continuously to control the action from moment to moment. Feedback control is usually used for slow movement and to maintain posture.


A Feedback control

B Feed-forward control

Figure 11 Feedback and feed-forward control circuits (Kandel et al 1991)

Feed-forward control (Figure 11 B), superimposed on the feedback loop, is essential for rapid movements and relies on advance information to adjust controlled variables. In catching a ball, advance information on the ball's trajectory and possible placement of the hand is received by sensors and fed forward by the controller. Through adaptive control, feed-forward control also monitors the system to deal with changes that take place over time, such as fatigue (Kandel et al 1991).

Basic movement types are (Krueger 2001):

- Posture control (e.g. holding the mouse in its place during clicking)
- Simple ballistic movements (e.g. single-clicking)
- Simple repetitive ballistic movements (e.g. tapping, typing, double-clicking)
- Complex ballistic movements from position A to B, including positioning at the end of the movement (e.g. pointing with the mouse)
- Adjustment of an object (e.g. drag-and-drop)
- Tracking with external control (e.g. a car race in a computer game)
- Tracking with internal control (e.g. hand-writing)
- Compensatory movement (e.g. swinging arms in walking)
- Reprogramming/correcting a movement during its execution (e.g. eye movement after detection of a typing error)

Complex movements integrate several of these types of action (e.g. position the mouse and click).

A schematic overview of the central nervous pathways in posture and motion is given in Figure 12. For better overview, some motor areas (cerebellum, basal ganglia, thalamus) have been left out and the representation follows a top-down view, disregarding the parallel interactions of all areas. The incentive to do a movement arises in the subcortical and cortical motivation areas. A strategy or plan how to realise the movement is made in the associative and sensory cortices. The motor cortex areas elaborate a detailed programme and select the spinal neurons. In the spinal cord, the motor neurons are recruited. At every stage, inputs from the sensory system and from the outside can interact with the systems. Sensory inputs include those from within the muscles.

The primary motor cortex (Figure 13) lies anterior to the central sulcus and is highly organised with respect to the anatomic pattern of responses. Different areas of the body are represented differerentially such that areas with fine motor control (fingers, speech apparatus) have a larger region of the cortex devoted to their function than areas with more gross control. The *primary motor cortex* determines the force exerted in individual movements. The direction of movement is governed by a balance of the forces generated by a population of cells in this area with different vectors of force generation. The function of the *premotor areas* is to prepare the motor systems for movement. The medial and superior part of the premotor area, termed the *supplementary motor area*, programmes motor sequences and coordinates bilateral movement. The lateral part of the premotor area, the premotor cortex, controls the proximal movements that project the arms to targets. The *posterior parietal cortex* is involved with the sense of the body in space.

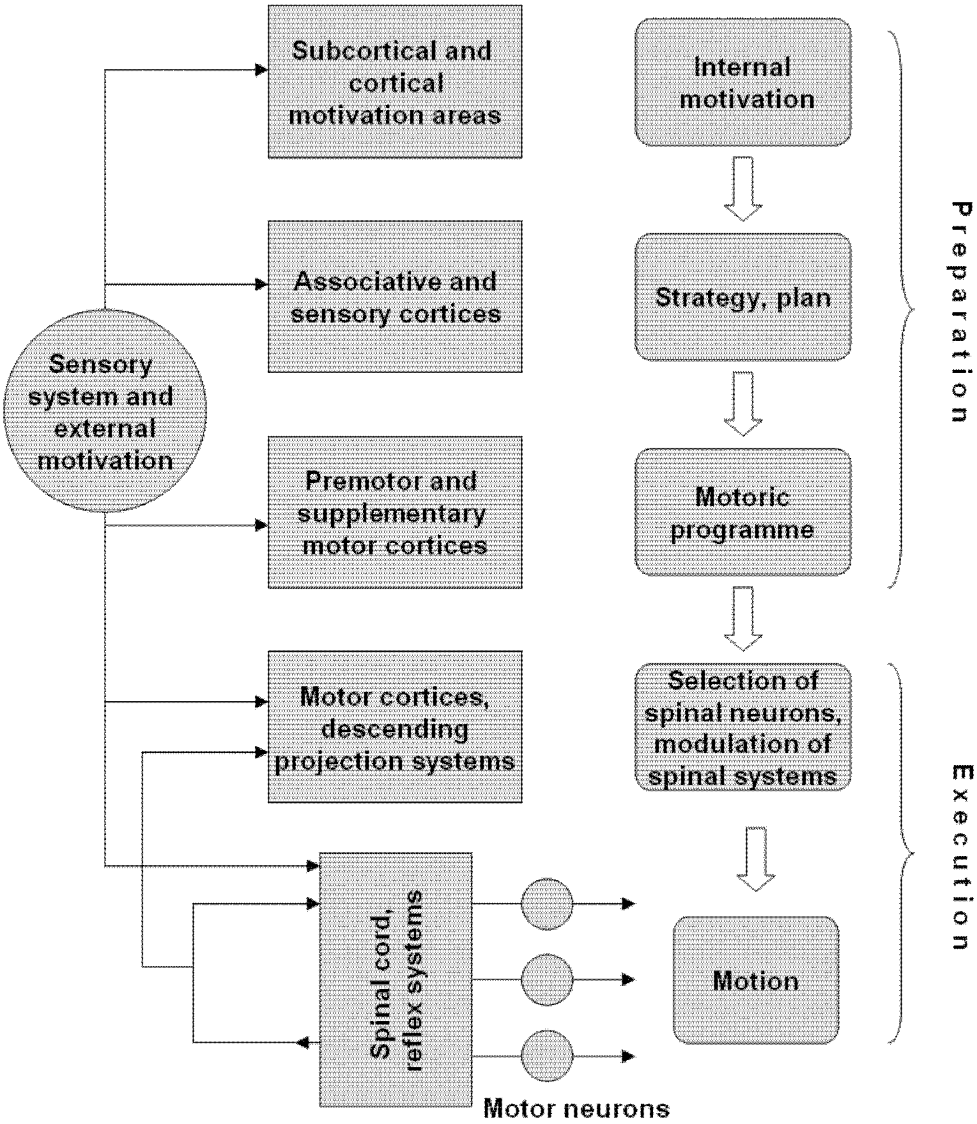


Figure 12 Central nervous pathways in posture and motion. For better overview, some motor areas (cerebellum, basal ganglia, thalamus) have been left out and the representation follows a top-down view, disregarding the parallel interactions of all areas (after Schmidt and Thews 1990)

Subcortical loops form between the motor cortices and the basal ganglia. The basal ganglia are a series of sub-cortical nuclei, including the caudate and putamen (together called the striatum), the globus pallidus, the substantia nigra and the subthalamic nucleus, all forming connections with one another. The basal ganglia are involved in the control of extremity and eye movement, the valuation and processing of sensory information and the behavioural adaptation to emotional context and motivation. In humans, the basal ganglia are recognised to be important regions for motor programme generation. The basal ganglia contain 80% of the dopamine present in the brain, and the more common movement disorders (e.g. Parkinson's disease) affect this system.

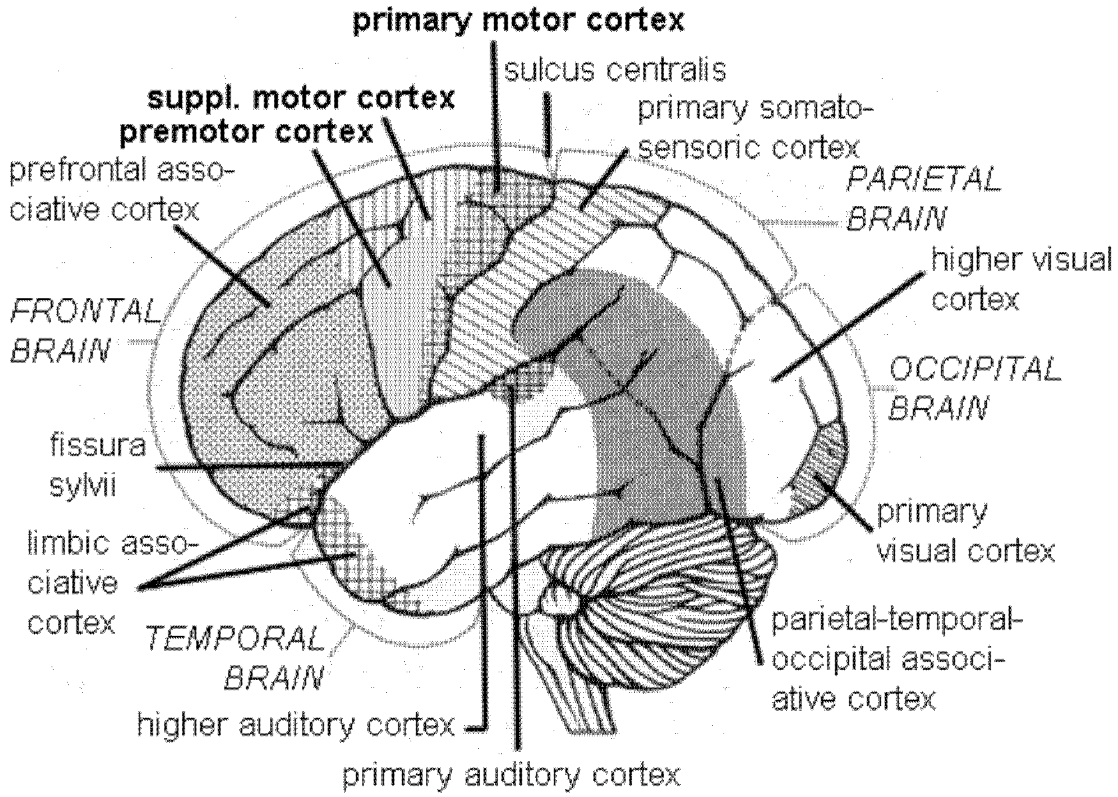


Figure 13 Areas of the human motor cortex (Schmidt and Thews 1990)

The cerebellum is the other major sub-cortical structure the motor cortices form loops with. It has two-way connections with the spinal cord, brainstem nuclei, the nuclei of the basal ganglia, and the cerebral cortex. The principal role of the cerebellum is in coordination of motor activity, especially with rapid and fine movements. It also appears to be important in assimilating sensory information in order to predict future position of limbs in dextrous movements. Inhibition of the brainstem reticular formation is via the cerebellum and the basal ganglia, and it is through these centres that information from the cerebral cortex is relayed to the brainstem in order to make any reductions in postural muscle tone that are necessary for voluntary movements.

The pyramidal system, bypassing the brainstem, carries impulses from the cortical motor fields to the primary motor neurons of the spinal cord and their related interneurons and is especially important for the control of finely tuned voluntary movements. The primary motor neurons and premotor interneurons, forming the basis for spinal reflexes and basic motor patterns, are modulated by the descending supraspinal pathways of the pyramidal and several extrapyramidal tracts.

4.5 Electromyography

Electromyography is a technique to measure, visualise and analyse the electric activity of muscles. It is being used in the diagnosis of neuro-muscular diseases, in sports medicine, and in work related medical fields.

4.5.1 History

Man has been interested for a long time how movement in humans and animals originates. Da Vinci e.g. (around 1500) did think about this thoroughly. Andreas Vesalius is known as the ‚father' of modern anatomy. In his book ‚Fabrica' he published sketches without references to the function. The Italian Francesco Redi speculated for the first time about a connection between musculature and electricity by assuming the origin of electric shocks of the electric fish in its muscles. Galvani (18th century) realised a connection between muscle movement and electricity and conducted experiments with frogs. His work ‚De Viribus Electricitatis' can be seen as the hour of birth of neurophysiology. But only in 1838 Carlo Matteucci succeeded in giving the evidence that it is electric currents that flow through muscles. About ten years later the French Du-Bois-Reymond described with the aid of a galvanometer voluntarily provoked movements of muscles by electric signals. He realised that the skin is an electric resistor, and that is why he did put his electrodes directly on open wounds which he had inflicted upon himself.

Up to then the inert galvanometer was used to detect electric currents. The invention of the Braun cathode ray tube (CRT) changed science in a revolutionary way by providing the possibility to detect alternating current. Still it took another 20 years until Gasser and Erlanger described and interpreted action potentials with the aid of the CRT. That got them the Nobel prize in 1944.

The inverse way, stimulating muscles through electric voltage, was used often in the nineteenth century. This was relatively easy to do and was used by charlatans to provide ‚miracle' healings. There were also serious scientists, especially the French Duchenne (in the middle of the 19th century), doing systematic research concerning the function of muscles. The first biomedical engineer, the Englishman Baines, described in 1918 the nervous system as an electric circuit consisting of resistors and capacitors.

In 1929 an intramuscular electrode was used for the first time by Adrian and Bronk. Buchthal and colleagues used these systematically in the 1950's and 60's. Around 1960 a wire electrode was used for the first time, and in Russia research started on controlling prosthesis by neural impulses.

4.5.2 Surface and intramuscular EMG

It is known as surface EMG if electrodes are attached to the skin surface. It is then the overall activity of the muscle that is being measured and no statement about the involved MUs can be provided (Gazzoni et al (2004) however did describe methods by which MUs can be identified with surface EMG). Obviously only superficial muscles can be measured. Furthermore they should not be too small or to near to other muscles (cross-talk). Surface EMG is used to measure whole (or large portions of) muscles and is being used if just the amplitude and the moment of activity is under question.

With intramuscular EMG it is not the whole muscle activity that is being detected but that of single muscle fibres, specifically those sufficiently near to the introduced electrode. By appropriate algorithms ('decomposition algorithms') it is being tried to determine the contribution of each MU. Intramuscular EMG is being used for two purposes: a) determination of the shape of the action potentials, e.g. in clinics, to show pathological changes and b) determination of the exact moments of the action potentials of each MU, thus making conclusions concerning their activity behaviour.

4.5.3 Monopolar and bipolar detection

With monopolar measurement the detection of the potential is between an active and an indifferent point, i.e. a distant and de facto field-free point. This referential point is e.g. a bone like the elbow. In intramuscular EMG the needle body can be used as the reference, too.

With bipolar detection two electrodes are applied over the same active zone. Each electrode measures the signal in relation to the point of reference. A differential amplifier subtracts one signal from the other, thus providing only the difference between electrode A and electrode B. The advantage of this procedure is that noise from the outside (electromagnetic fields or other biological signals) can be eliminated to a large extent, because the influence on both electrodes is about the same.

The disadvantage of bipolar measurement is that very small amplitudes are being measured when the distance between the electrodes is small, because the signal propagation times are short and the potential difference is low. If the electrodes are placed too far from each other, the measurement is of two different sources (different MUs) and would make no sense.

Monopolar measurement is used especially when the signal shape of a MUAP is of interest. In our experiments however the measurements were only conducted with bipolar electrodes.

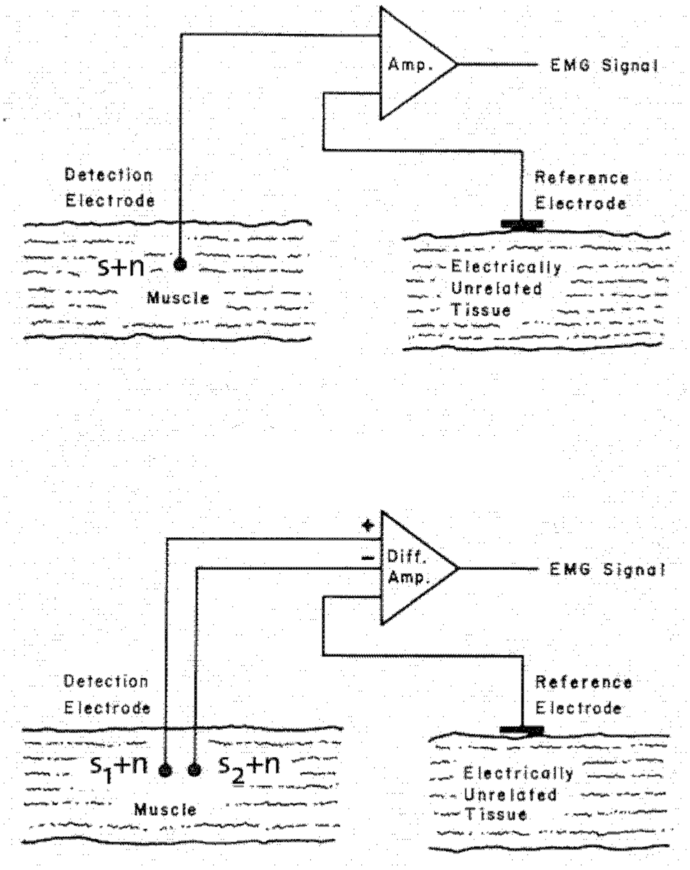


Figure 14 Top: monopolar recording. Bottom: bipolar recording (s: signal, n: noise) (Basmaijan and de Luca 1985)

4.5.4 Electrodes

Surface electrodes exist as single- and multiple-use. A multi-use electrode consists, e.g., of a metal plate of 5mm diameter made from an Ag/AgCl alloy, inserted in a round plastic casing. Attached to this casing is an adhesive ring. A firm and stable contact with the skin is very important. Hairs should be shaved. The upper, defunct layer of skin should be removed (a peeling sponge can be used for this). The skin is furthermore cleaned with alcohol. Before attaching, the gap between the metal plate and the skin is filled with conductive gel. For a bipolar measurement, a pair of electrodes is placed in a distance of 1-2 cm in the direction of the muscle fibres. A reference electrode is attached to a bony location, e.g. the elbow. If more than one muscle is investigated in the same experiment, one reference electrode is sufficient. The connections between the electrodes and the pre-amplifier are preferably set up by twisted cables.

Needle electrodes are used to record intramuscular EMG. Depending on the investigated topic, different implementations exist; the most important ones are depicted in Figure 15. Type A is a coaxial needle electrode (0.5 - 0.7 mm in diameter) with a single, relatively thick platinum wire of 25 - 150 μm, used for monopolar measurements (the needle body can be used as reference). Type B contains a second wire so that it can be used for bipolar measurements. For bipolar, differential measurements a surface electrode should be attached to a bony location far from the recording site. Types C through F contain fine wires that do not exit at the tip but on the side of the needle. With fine wires, fewer MUs will be detected. If a needle contains more than two wires, multichannel measurements are realisable (see below).

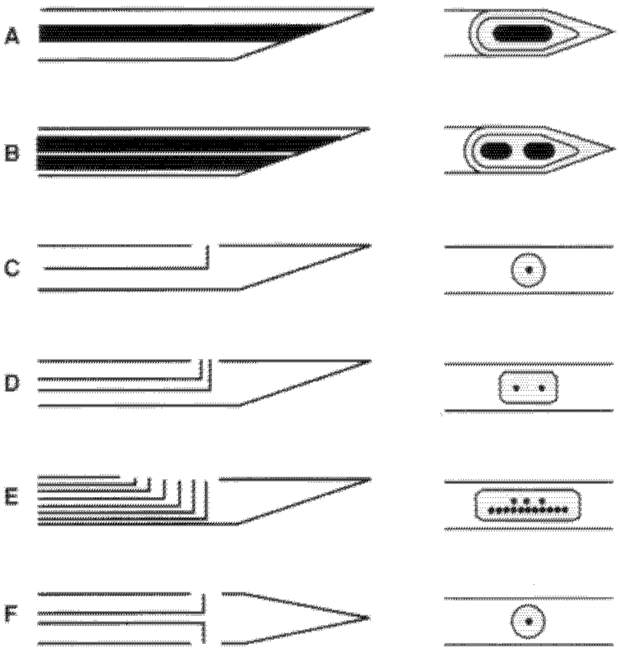


Figure 15 Different types of needle electrodes. : A: coaxial electrode (ø 0.5-0.7 mm) with single, thick platinum wire (ø 25-150 μm) for monopolar measurement. B: Like A, but with second wire for bipolar measurements. C through F: different types with fine wires, arranged laterally. Electrodes with fine wires will detect fewer MUs. C: monopolar, D: bipolar, E: multichannel.

Needle electrodes have two drawbacks: Their tip dislocates very easily with the slightest limb movement. Even if this occurs only by a tenth of a millimetre, the recording tips may already see different MUs. Prolonged measurements on the same MUs are thus hard to achieve. The other drawback is that the rigid needles can be painful during movements.

Wire electrodes cause less pain with movements and are less likely to dislocate due to their bent ends (barbs). They can easily be assembled with pieces of insulated fine wire (25 - 100 μm in diameter) slid through a hypodermic needle (Figure 16). The wires must be highly non-oxidative and have a certain rigidity. The tips should be de-insulated by no more than 1mm. We had good experience however with non-de-insulated wires, where the contact surface consisted only of the front cutting area.

The wires are bent at the needle tip in order to create a barb of 1-2mm. In the case of de-insulated wire ends any contact between the single bare ends must be avoided by using a staggered alignment. The other ends of the wires are de-insulated by 1cm approx. in order to insert them into the clamps connecting to the amplifier at a later stage. As soon as the needle has been properly positioned in the muscle, it is pulled out gently while making sure that the wires are kept in place with the aid of the barb. The needle is completely removed before connecting the wires to the clamps. Once inserted, the wires are hardly noticeable and, thanks to their flexibility, they are less prone to shifting with limb movements than a needle. After having accomplished the measurements, the wires can easily be removed by a gentle pull.

The drawback of the wire electrode is that its positioning is a matter of hit or miss. Neither is it possible to check for motor unit action potential trains during positioning, nor can the position be altered to find a site with better signals after having established a connection to the amplifier. It is suggested to contract the limb several times after insertion and connection of the electrode and before starting the recordings, in order to increase the probability that the detection surfaces are kept in place.

A technical limitation with the wire electrode is that the exact spatial relationship of the detection surface is unknown. It should however be possible to manufacture electrodes with wires glued together to achieve a defined distance between the wire tips.

Cleanliness and sterility are crucial with any type of intramuscular electrode. Multi-use needle electrodes require, apart from sterilisation, special treatment to thoroughly remove any tissue remainings. Sterilisation is best achieved by autoclaving; single-use electrodes can alternatively be kept in 70% alcohol overnight.

Incidentally, bad conductivity was observed during our first tests with wire electrodes. We assumed that partial oxidation occurred at the wire tips during sterilisation in alcohol despite the highly non-oxidative material used. This was solved by leaving the wire ends somewhat longer during the manufacturing and cutting them to the final length with sterilised scissors just before inserting them in the muscle (Figure 17). This procedure can of course only be applied to non-de-insulated wire ends. Cutting the bundle of wires with one cut at a 45° angle will enlarge the detection surface and also increase the inter-wire distance.

4.5.5 Amplification, filtering, sampling and recording

The very week EMG signals in the range of some 100 µV need to be amplified to practical dimensions. Be s the signal and n the noise whose sources are far from the electrodes, then, with monopolar recording, the amplified signal V will be equal to V = G(s+n) with G = gain. With bipolar recording and differential amplification, s1 being the signal from electrode 1 and s2 that from electrode 2, V will be V = G(s1+n) - G(s2+n) = G(s1-s2). The external, ‘common’ noise n, that is ‘far’ from both electrodes and has thus more or less the same level at both sites, will be eliminated. The 'common mode rejection ratio' CMRR is one of the quality criterions of an amplifier, indicating how much of the common noise is eliminated.

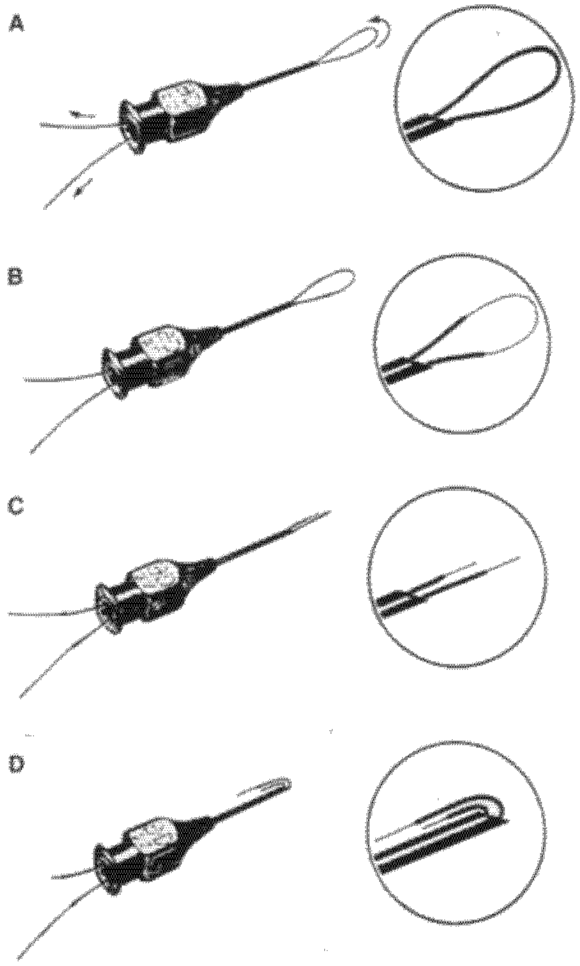


Figure 16 Manufacturing of a bipolar, one-channel wire electrode with de-insulated tips (Basmaijan and De Luca, 1985)

To reduce induction effects on the connections between electrodes and amplifier a pre-amplifier of small size, placed near the electrodes and typically fastened to the subject, can be used. Pre-amplified signals will be less susceptible to induction effects. In our setting though a 'guard-drive' (description in: Analog Devices, 1999) technique was used (T. Schaerer, ETH Signal and Information Processing Laboratory (ISI)), which avoids pre-amplifiers attached to the body or dangling from the neck.

Amplifiers are usually equipped with filters. A high-pass filter at about 20 Hz eliminates the DC component (originating e.g. from the transition between electrode and conductive gel) and artefacts that can be caused by movements. A notch filter is a narrow band filter that removes the 50 Hz mains frequency. A low-pass filter is crucial with digital recordings in order to meet the Shannon theorem (see below).

Because a computer can only process time- and amplitude-discrete values, signals have to be sampled for digital recordings. This is called A/D (analogue/digital) conversion and means that the signal is measured and stored at periodic intervals of, e.g., 1 ms. Sampling is usually achieved with an A/D conversion card. The sampling frequency depends upon the application, the frequencies expected, the frequencies needed, and the filtering.

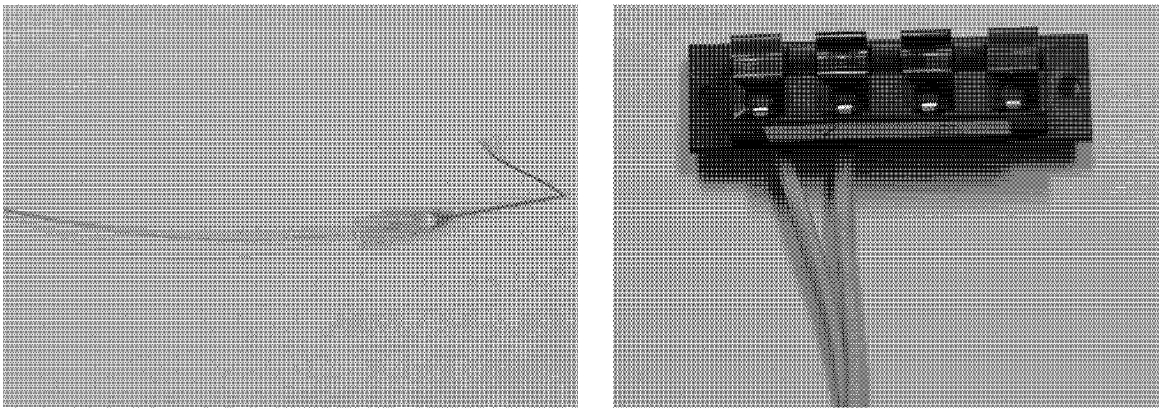


Figure 17 Wire electrode with 4 fine wires and clamps to connect to amplifier used in the experiments

The Shannon theorem claims that the sampling rate be greater than twice the highest frequency contained in the original signal (after filtering). This is why low-pass filtering (in the context of A/D conversion also called anti-aliasing filtering) is crucial – if signal frequencies higher than half the sampling frequency were passing to the sampler, severe artefacts would occur. Depending on the quality of the low-pass filter, a certain safety margin has to be included. With surface EMG one is usually interested in the frequency range between 20 and about 400 Hz (higher frequencies are eliminated by the skin filtering properties). The low-pass filter could then be set to 400 Hz and the sampling rate to 1000 Hz, leaving a safety margin of 200 Hz. Higher frequency components are required (and can be attained, as there are no skin filtering effects) with intramuscular EMG, so that the low-pass filter is maybe set to 6 kHz and the sampling frequency to 20 kHz. After the sampling, the signal can be stored on the computer's hard drive.

EMG signals can be interfered by various sources, such as:

- electromagnetic fields caused by mains (50 Hz and first harmonic at 150 Hz)
- electrostatic fields e.g. caused by synthetic textiles
- fields from other biological sources, such as other muscles (including the heart)
- noise by resistors in the recording chain and by the semi-conductors of the amplifier
- thermal noise of the electrodes
- amplitude attenuation by approx. 25% per 0.1 mm of human tissue
- low pass filtering by skin and fatty tissue
- high pass filtering at transition between electrode and conductive gel
- decrease of pH within the muscle with fatigue (change of ion concentration)

- motion artefacts at electrode - muscle transition (polarisation potential by contact of two materials; a current is generated by moving the materials in relation to each other)
- skin potential of approx. 20 mV, changing with skin movement
- motion artefacts of cables between electrodes and pre-amplifier (a conductor moved in an electromagnetic field provokes a current, leading to high voltages because of high amplifier input resistance (V=Z*I))

4.5.6 Analysis of surface EMG

The raw EMG (example in Figure 18) is usually smoothed and rectified. Often root mean square (RMS) is applied with a moving window of, e.g., 50 ms. If necessary, a constant noise offset can be subtracted, measured during complete relaxation of the muscle. Next, a surface EMG is usually normalised, i.e., divided by a standard EMG value, which is either the value obtained during maximum voluntary contraction (MVC), or that during a defined static contraction such as extending the arm horizontally (in a shoulder muscle measurement). The reason for this is that the voltages measured can vary highly between single measurement sessions and subjects. The voltage depends, among other, on the exact electrode placement, the contact properties between skin, contact gel and electrodes, the thickness of skin and fat layers and skin moisture. Reference measurements are usually executed before and after an experiment to compare for consistency. The EMG values are then given in relation to the reference measurement. The notation used in this text is %MVE ('percent of EMG measured during MVC') (Figure 18).

After the normalisation the EMG is ready for further analysis, such as mean and percentile computations (see below).

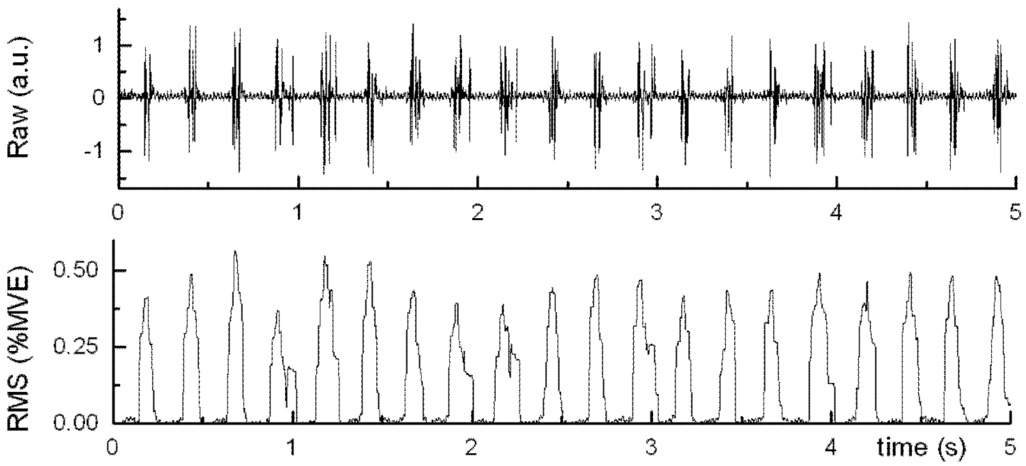


Figure 18 Example of a surface EMG. Top: raw EMG (arbitrary units); bottom: after root mean square and normalisation to %MVE.

4.5.7 Analysis of intramuscular EMG

The methods of intramuscular EMG analysis depend on the questions asked and are basically the same for measurements with needle and wire electrodes. Clinical diagnosis is often interested in the shape and shape changes of MUAPs to find degenerative processes. This is achieved by identifying single MUAPs and measuring their parameters such as steepness, amplitude, duration, area, number of peaks and irregularities. In our context however we're primarily interested in a precise description of the moments of firing of as many MUs as possible. This means that the recorded signal, containing the overlapped firing trains of many MUs, has to be decomposed, based mainly on the shape properties of the superimposed action potentials of the constituent MUs. This is not a trivial problem, and until a few years ago it was only possible to analyse signals with a duration of a couple of seconds and low activity (few involved MUs), taking typically many hours of manual work. In the present experiments the durations could be extended to 9 minutes and since the completion of the experiments, our research group, in conjunction with the ETH Signal and Information Processing Laboratory (ISI), could extend them to more than 30 minutes.

The general procedure of the decomposition is to first detect the sections in the filtered signal (Figure 19-1) with a minimum of activity. These 'active segments' (2) are stored. With heuristic methods the active segments are determined that are formed by just one MUAP. Those composed from two or more MUAPs are not regarded for the moment. Similar MUAPs are postulated to derive from the same MU and denoted as templates (3); however, depending on the contraction state of a muscle, the shape of a MUAP can vary through time. A first firing statistic can now be made for the non-overlapping MUAPs (4).

To decompose the overlapping segments, combinations of two or more templates have to be tried out systematically. As overlapping MUAPs do not necessarily start at exactly the same time, the combinations of templates must be performed with all possible time shifts, leading to a fast increase in computational power when combining three or even more templates.

With long term measurements the MUAP shape can (permanently) change due to electrode displacement in relation to the muscle fibres (especially after muscle contractions), electrical interferences, physiological changes or other reasons. If a MU is active during such a shape change, it is likely to be further tracked. If, however, the MU is pausing, or the shape change is abrupt (by electrode displacement, e.g.), it may be misclassified as a new MU after the pause.

Wire-electrode recordings are generally of inferior quality than signals detected with a needle (lower signal-to-noise ratio and bandwidth, more similarities in MUAP waveforms). This is why often three-channel instead of one-channel recordings are performed (using four wires, one of which is the common reference). This way a MUAP is seen from three different positions with different waveforms, which gives more exploitable signal information.

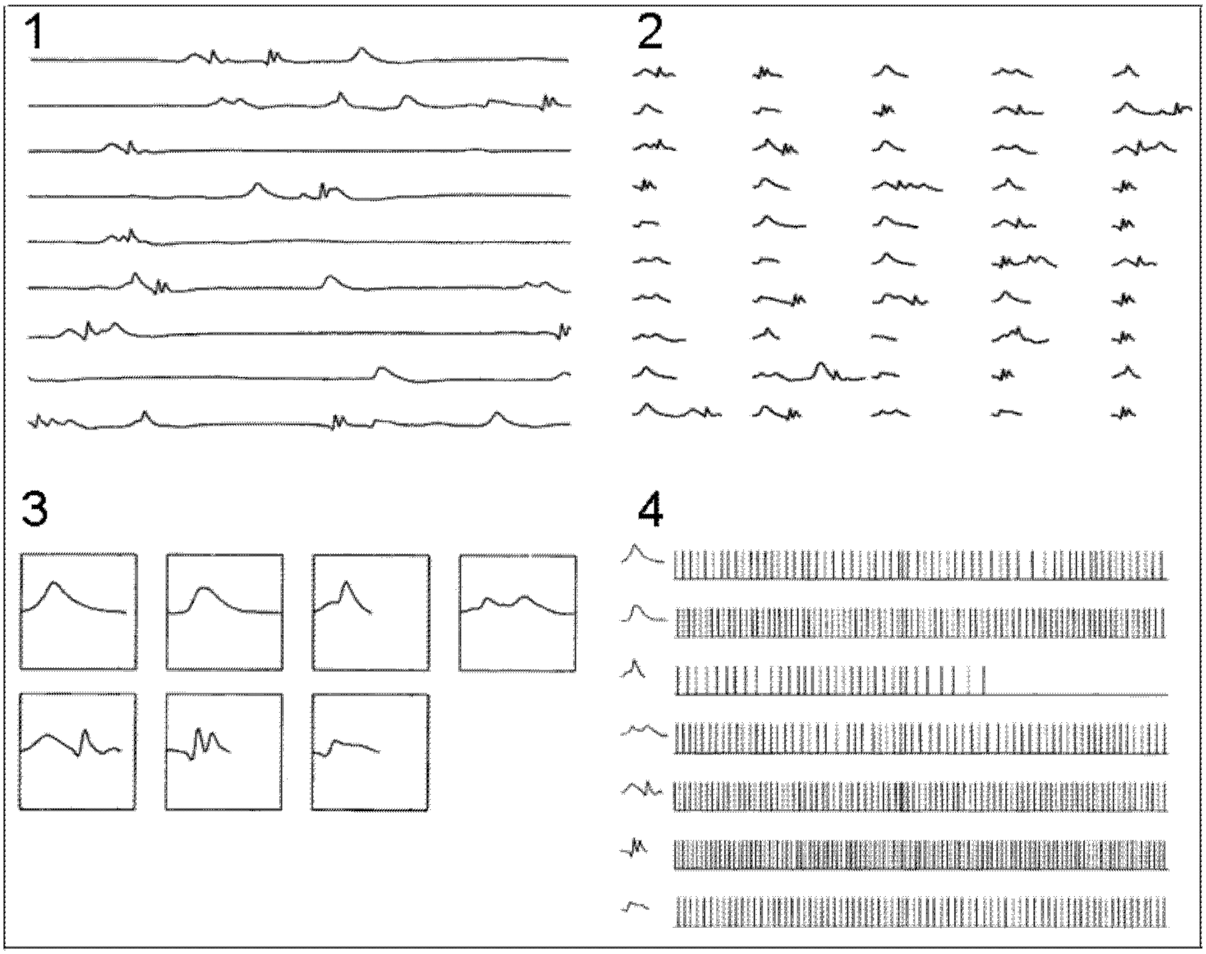


Figure 19 Principle scheme of intramuscular EMG decomposition (one channel). 1: measured and filtered EMG signal (plotted over several lines). 2: segments of the EMG signal with a minimum of activity ('active segments'). 3: template postulation. 4: firing statistics (only non-overlapping MUAPs)

4.5.8 MAPQuest / MAPView

The decomposition of the intramuscular EMG recordings of the present experiments was realised with two software packages that emerged from the long-time research in this field at the ETH Zurich Signal and Information Processing Laboratory (ISI): MAPQuest/MAPView and EMG-LODEC. Based on the research of Gut (1992), who uses the so-called Viterbi decoder (Gut and Moschytz 2000, Proakis 1995), Wellig realised MAPQuest (Wellig and Moschytz 1998). MAPQuest is limited to single-channel EMG signals up to 10s duration and works in three steps:

Step 1: In the *segmentation phase*, active segments are determined based upon thresholds that can be set individually for the beginning and end of the segments, depending on the signal quality. As the output the algorithm marks all signal segments that have been determined active. These segments can contain non-overlapping MUAPs, slightly or fully overlapped MUAPs, and artefacts.

Step 2: During the *incomplete decomposition*, the active MUs and the MUAP templates are determined. Only non-overlapping MUAPs are considered in step 2. They are classified by means of the single-linkage clustering nearest neighbour method (Haas and Meyer 1989). The minimum number of segments per cluster can be set by the user. In the present experiment 2 it was set to five, thus MUs with less than five firings within a 10 s segment were not considered. During step 2, intervention is possible to manually combine two templates that the user believes to belong to the same MU. This was applied very carefully in experiment 2, using information from the other channels and firing patterns. Templates with low magnitude were not systematically dismissed but kept until the end in order to find as many MUAPs as possible.

Step 3: In the third step, the *complete decomposition*, the segments with overlapping MUAPs are decomposed. This is where the Viterbi algorithm sets in: the superimposed waveform is modelled as a signalling system with inter-symbol interference, which encodes a well defined sparse information sequence. The algorithm decodes this sequence and calculates the most probable combination of waveforms (MUAPs) in a very efficient way. No new postulations of templates are made at this stage, and the template shapes are kept constant for the whole file length.

MAPQuest was successfully used in the present experiment 2 with three-channel recordings and durations of 180 s. Because MAPQuest can only decompose one-channel signals of 10 s, the long recordings were split to segments of 10 s and analysed channel by channel, making up for 3*18 single files. The results of the three channels were first manually compared to find and correct misclassifications. They were then processed with MAPView, a Matlab tool that we have developed to combine the single results, comparing MUAP shapes and inter-spike-intervals.

4.5.9 EMG-LODEC

The next software development at the ISI laboratory was EMG-LODEC (Wellig and Moschytz 1999). With EMG-LODEC, three-channel recordings of long duration can be decomposed. The programme is a combination of the sequential analyses method by Erb (1978) and Studer (1984) and the block oriented method by Gerber (1984), Haas (1989) and Gut (1992). It uses segmentation and incomplete and complete decomposition stages similar to MAPQuest. The block oriented method is used to identify newly recruited MUs, the sequential method to classify earlier detected MUs and to update the reference signals. EMG-LODEC works on three-channel recordings but does not stop when one or two channels are missing, or set off and on during a recording.

EMG-LODEC uses wavelet transforms. Like other transforms (Fourier-, Laplace- or Z-transform), the wavelet transform transfers a periodic or singular waveform f(t) from the time domain to the frequency domain G(Ω). The solutions found in G(Ω) can then be transformed back to the time domain. The wavelet transform decomposes a signal into a weighted sum of basic functions that are dilated and translated versions of a prototype function called the mother wavelet (Mallat 1998). While the Fourier transform uses fixed-sized time windows, these are variable in the wavelet transform. Low frequencies are analysed over wide time windows and high frequencies over narrow windows. Wellig could show that a great part of the signal energy and the information needed for template discrimination is concentrated in only a few (low frequency) wavelet coefficients, which results in a high compression rate. He realised an efficient numeric implementation of the wavelet transform using multi-scale analysis. The problem of MUAP waveform changes over time is overcome by regular template updating.

5 Techniques

The main tools to explore the brought up questions were surface and intramuscular EMG. This chapter explains the surface and intramuscular EMG methods and techniques used in the experiments. See also (4.5) for common EMG techniques. Methods only used in a specific experiment will be described there.

5.1 Surface EMG methods

Surface EMG (S-EMG) was collected in all experiments from up to six locations of the finger, upper arm and trapezius muscles, namely:

- m. extensor digitorum communis (finger extensor, EXT)
- m. flexor digitorum superficialis (finger flexor, FLE)
- m. biceps brachii (biceps, BIC)
- m. triceps brachii (triceps, TRI)
- m. trapezius pars descendens (trapezius p. desc., TRD)
- m. trapezius pars transversa (trapezius p. transv., TRT)

5.1.1 Electrodes

Pairs of Ag/AgCl electrodes were attached to the muscles, and a reference electrode to a bony location on the elbow or sternum. On the forearm the electrodes were attached on the radial (EXT) and ulnar (FLE) side at 1/3 of the forearm length (measured from the elbow), above the points of highest activity when tapping with the index finger. The point was found by palpation. The upper arm electrodes were attached on the most bulky area of the BIC and TRI muscle. The centre of the electrodes on the TRD was 2 cm lateral of the midpoint between C7 and acromion; on the TRT it was on the midpoint between the spinal processi and the medial edge of the scapula.

The round multi-use electrodes (ø 5mm, type Beckmann) were attached with a centre-to-centre distance of 20 mm over the EXT, FLE, TRD and TRT. For the bulkier BIC and TRI a slightly larger type of rectangular shape was chosen (Biotrace HR single-use, Ag/AgCl, 15x20 mm, 40 mm centre-to-centre distance). The skin was gently abraded with a peeling sponge and cleaned with alcohol prior to the application of the electrodes (Basmaijan and De Luca, 1985).

5.1.2 MVC and MVE

All MVC measurements were realised with isometric contractions. For the FLE this was achieved by pressing the index finger against the desk surface, while the experimenter grasped the subject's wrist firmly and fixed it in place. For the EXT, the index finger was extended against the experimenter's hand. For the BIC, the subject placed the elbow on the table surface with a semi-supinated hand and an arm flexion of about 90°. The experimenter fixed the forearm while the subject tried to flex the arm. For the TRI the subject pressed the hand against the desk surface. For the TRT the subject stood up, raised the arms in front of the body to shoulder-height, clutched the fingers of both hands firmly and pulled the arms backwards and apart. For the TRD, the subject was standing while grasping a handle with the right hand that was fixed to the floor by a chain. The chain was adjusted so as to ensure a contraction with an upright body, pulling the shoulder upwards.

The MVC/MVE recordings were repeated three times with the same muscle with some seconds rest in between, and again three times at the end of the experiments. The subjects were verbally encouraged to contract with their utmost possible force.

5.1.3 Amplification, filtering and recording

Two different amplifiers were used to process the EMG signals:

- Amplifier 1 was a high-class, 4-channel amplifier with guard-drive. The settings for S-EMG were: high-pass filter 30 Hz, low-pass filter 300 Hz, notch filter 50 Hz (T. Schaerer, ETH Signal and Information Processing Laboratory; see also 5.2).
- Amplifier 2 was a 16-channel device with low-pass filter (-3dB/oct, set to 490 Hz) and high-pass filter (set to 5 Hz), but no notch filter (Toennies, Würzburg Germany).

Amplifier 1 had better amplification and filtering characteristics, but only four channels. It has primarily been developed for I-EMG, but was also used with S-EMG whenever there were available channels. In experiment 1 (no I-EMG), amplifier 1 was used for the EXT, FLE, TRD and TRT muscles, and amplifier 2 for the BIC and TRI. In experiment 2 and 3, the spare channel of amplifier 1 (I-EMG needed 3 channels) was used for the TRD S-EMG, and amplifier 2 for that of the EXT and FLE. The amplification was set individually for each recording, depending on the actual signal power, and written down. It was typically between 2.000 and 10.000 for S-EMG.

A 12-bit A/D card from National instruments was installed in a 350 MHz personal computer with Microsoft Windows NT 4.0 in order to sample and store the EMG data.

A programme was written in LabView™ to this purpose. The sampling frequency was set to 980 Hz in experiment 1[1] and 1000 Hz in experiment 2 and 3[2].

5.1.4 nRMS calculation

Another LabView™ programme was used for the digital post-filtering to eliminate mains harmonics (50 Hz and multiples) from the signals processed with amplifier 2. From these EMG signals x_t ('raw EMG'), RMS (root mean squared) values $\bar{x}'_t$ were computed by rms-averaging over a moving window of 50 ms length (49 or 50 data points, respectively):

$$\bar{x}'_t = \sqrt{\frac{1}{n}\sum_{\tau=t}^{t+n-1} x_\tau^2} \quad \textit{(n=49 or 50, resp.)}$$

The MVC/MVE signals were averaged with the same method. Additionally they were (linearly) averaged over a 1 second moving window (Martin et al, 1996):

$$\bar{x}_t^{mvc} = \frac{1}{m}\sum_{\tau=1}^{m-1} \bar{x}'_{t+\tau} \quad \textit{(m=980 or 1000, resp.)}$$

The maximum value x_{mvc} from this time series was used as the reference MVE:

$$x_{mvc} = \max(\bar{x}_t^{mvc}) \quad (\text{all } t)$$

The MVC/MVE assessments were repeated at the end of the experiments and the largest of all x_{mvc} used. Dividing the RMS signals by x_{mvc}, standardized RMS EMG signals $\bar{x}_t$ ('nRMS') were obtained:

$$\bar{x}_t = \frac{\bar{x}'_t}{x_{mvc}}$$

In the subsequent text, the term 'EMG' always means the standardised nRMS signal $\bar{x}_t$, written as '%MVE'.

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[1] A multiple of 140Hz. This was due to a different experiment conducted at the same time that contained equipment with this fixed frequency.

[2] Actually the signals were recorded with 10 kHz in experiment 2 and 20 kHz in experiment 3 because of the simultaneously recorded intramuscular EMG. Later, the S-EMG signals were downsampled to 1000 Hz.

5.1.5 Static and dynamic activity

Percentile values to describe muscle activity are a widespread measure in EMG analysis and have for example been used by Jonsson (1982) or Müller et al (1988). In the present experiments the 5th or 10th percentile (P5/P10) was used as a measure for static, ongoing activity. The 90th or 95th percentile (P90/P95) was used for the dynamic (or phasic) activity contained in repetitive muscle activation. The 50th percentile (P50 = median) indicated an average activity.

5.2 I-EMG methods

Intramuscular three-channel wire-EMG was recorded and analysed in experiments 2 and 3 from the TRD of the right body side. A four-wire electrode as described in the background chapter was inserted 20 mm medial to the midpoint between the C7 spinous processus and acromion. The insertion point was in the middle between the two electrodes used for bipolar S-EMG measurement.

The four-wire electrodes were manufactured as described in 4.5.4. The wire (Science Products, Hofheim Germany) was from stainless steel with a diameter of 60 µm, coated in a Teflon insulation, making up for a total diameter of 80 µm. The four wires of about 15cm length were threaded through a 26G hypodermic needle and twisted at the tip, leaving several millimetres of spare wire (Figure 17). The spare wire was to be trimmed to 1-2mm at a 45° angle with scissors after sterilisation, before their inserting into the muscle. This resulted in a staggered alignment of the wires in relation to each other. Sterilisation was achieved by keeping the electrodes in 70% ethanol during 12 hours (in experiment 2), or by autoclaving during 15 minutes at 125°C and 1.2 bar (in experiment 3). No de-insulation was applied and the detection area of a wire consisted only of the exposed tip of $R^2\pi(\sqrt{2}+1) \approx 45 \cdot 10^{-5} mm^2$.

The subject's skin was slightly anesthetised with chloromethane spray before inserting the needle with a 45-60° angle and a depth of about 15 mm (Basmajian and De Luca 1985). After insertion and withdrawal of the needle, the wires were fixed to the skin by auto-adhesive tape leaving a loop, so there was some spare wire that could be pulled into the tissue during the first muscle contractions and body movements. The reference electrode was placed over the sternum or spinous processus.

The connection of the very thin wires to the thick ones leading to the amplifier was achieved with simple loudspeaker clamps obtained from an electronics supply shop (Figure 17). Attempts with specialised, expensive fine clamps were less successful. One of the four wires was used as the common electrode, to which the three voltages were referenced to. A test with an impedance meter, specifically designed for wire electrode testing (T. Schaerer, Signal and Information Processing Laboratory (ISI)), gave a first impression if reliable signals could be expected. A reasonable impedance of a wire electrode should be between 50 and 250 kΩ. If the test was successful, the leads were connected to the amplifier. If three channels with good signal quality were present, the experiments could immediately start. If there were less than three good channels, a different wire was chosen for reference. This procedure was repeated if necessary. If not at least two good channels could be found, the subject was asked if he/she agreed that a new attempt with a fresh needle electrode was undertaken – if not, the experiment was stopped and the subject released.

The differential amplifier (amplifier 1 in 5.1.3) was specifically designed for I-EMG. It contained a four-channel pre-amplifier with guard-drive leads (description in: Analog Devices, 1999) connecting to the electrodes. The main device contained high-class low-pass filters in switched-capacitor technique (-100 dB/oct). Notch filters in switched-capacitor technique and a PLL frequency multiplier filtered out the 50 Hz mains frequency following mains fluctuations exactly. The high-pass filters were built in active RC technology.

The amplification was typically between 10.000 and 20.000 and set individually for each recording, depending on the actual signal power. In experiment 2 the sampling frequency was set to 10 kHz, the low-pass filter to 3 kHz and the high-pass filter to 30 Hz. In experiment 3 the sampling rate was increased to 20 kHz and the low-pass filter to 6 kHz. Sampling and recording was achieved together with the S-EMG as described in 5.1.3. Signal decomposition was accomplished with MAPQuest and MAP-View in experiment 2 (see 4.5.8) and with EMG-LODEC in experiment 3 (4.5.9).

6 Experiment 1

Effects from finger tapping on upper arm and trapezius activity

A finger tapping study was the first in a series of three experiments. Seven male and two female subjects participated and performed tapping tasks with the index finger at five fixed rates between 2 and 6 Hz and at their individually chosen optimal and maximum possible rates. The body posture was varied between upright, slightly reclined and leaning forward. The conditions were presented in a randomised and balanced order. The last task was to tap at 5 Hz and upright posture for as long as possible, that is, until exhaustion. The aim was to find if co-activity was induced in the trapezius and upper arm muscles, and how it depended on the different conditions. Surface EMG was measured from the finger extensor and flexor, triceps, biceps, and the trapezius pars transversa and descendens, as well as the force on the rigid key used for tapping. The EMG was root-mean-squared and normalised to MVE and the following parameters were computed: 5th, 50th and 95th percentile (for static, median and dynamic activity, respectively), effective tapping rate, tapping steadiness, mean key force, and the auto-correlation of the EMG at a lag of one median keystroke interval as an estimate for the amount of synchronisation between co-activity and finger movements. It was found that already at subjectively comfortable keying rates, and sometimes even during relaxation, low to high co-activity was constantly present in the upper arm and trapezius muscles in a part of the subjects. Co-activity increased with fast tapping and a leaning forward body posture and decreased with a slightly reclined posture. However the outcomes varied strongly between individuals, and certain subjects did not co-activate their muscles at all. From this it can be concluded that trapezius and upper arm activation is not necessarily required for a simple finger tapping task with little mental demand and that some persons, possibly susceptible ones, are using their neuromotor system in a sub-optimal manner. This may explain why some computer users are developing WRMD, while others remain healthy.

6.1 Objectives

In the first experiment the impact of simple finger tapping on trapezius and upper arm co-activity was investigated with surface EMG (S-EMG). In a similar setting with finger tapping during 5 sec at different rates and an upright posture, measuring the interaction of extensor digitorum communis and flexor digitorum superficialis, Weiss (1998) had found a strong dependence of the activity levels and the antagonistic synchronisation on the tapping rate. With tapping rates up to about 4 Hz the two antagonists were interacting using a 'co-operative' antagonism, whereas at higher rates the antagonism became 'competitive'. Slow tapping was mainly executed with the extensor; with increasing rates the flexor participated in the movement and the extensor kept some activity during longer time or even the whole phase due to a lack of relaxation time.

The objective here was to seek for co-activity in the trapezius and upper arm muscles and to learn, what impact variation of tapping rate and sitting posture had. The posture was altered between three positions allowing a more relaxed or constrained neck and shoulder in order to see if co-activity is linked to postural adaptation processes. The course of co-activity was also of interest, i.e., if it was steady or cyclic, and synchronized with the finger muscle activity or independent. Changes in co-activity when the finger muscles attained temporary exhaustion were to be observed by conducting one tapping task for as long a period as the subject was able to. The tapping steadiness and finger force were collected to see if they were in any way linked to the co-activity parameters.

The following hypotheses were formulated:

- Finger tapping will induce static and dynamic co-activity in the upper arm and trapezius muscles.
- Individual outcomes will vary strongly due to individual motor strategies and/or susceptibility.
- A moderate, self-determined tapping rate will induce lower co-activity levels than a predetermined, high rate with competitive finger muscle activation
- These levels will also be increased with very slow tapping (finger floating, thus increased extensor activity)
- A part of the trapezius activity will originate from postural adaptation and be reduced when the subjects assume a comfortable, slightly reclined posture, and increased when they lean forward
- Subjects developing high finger muscle activity will be exhausted more rapidly
- A fatigue-related increase of finger activity will be mirrored as an increase of trapezius and upper arm co-activity

6.2 Procedures

6.2.1 Subjects and workplace

Seven male and two female subjects between 24 and 39 (29 ± 4) years gave informed consent to participate in this study. All were right-handed, healthy, and did not suffer from musculoskeletal disorders. Approval for this study was obtained from the ethical committee of the University Clinic of Zurich.

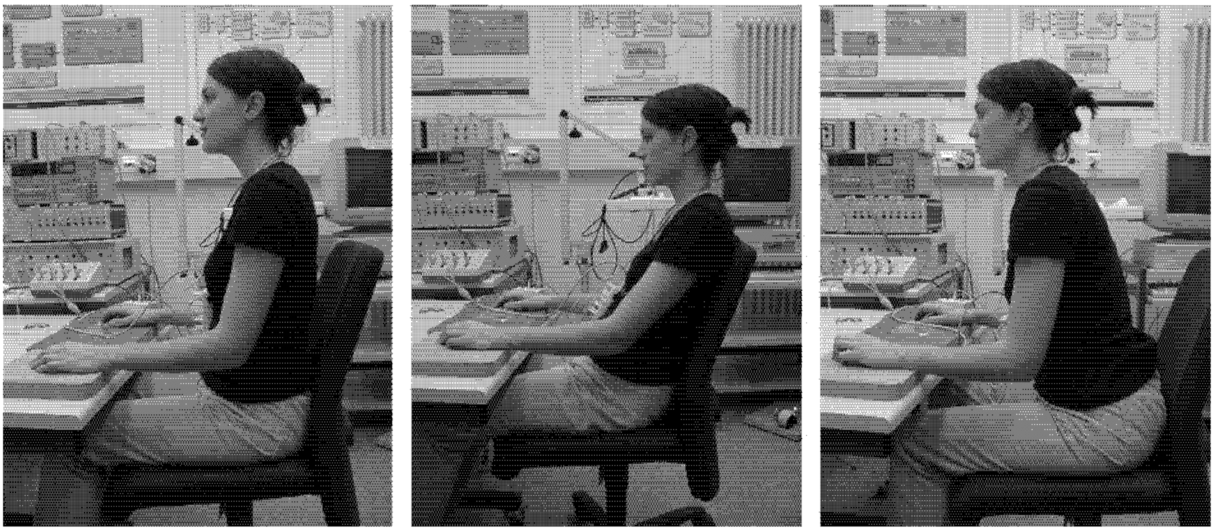


Figure 20 The three body postures assumed during the experiment. Left: pos. U (upright); middle: pos. R (slightly reclined); right: pos. F (leaning forward)

The subjects were sitting on an ergonomic office chair with a back support of medium height (Girsberger). The heights of table and chair were adjusted so that when sitting upright the upper arms were hanging down in a natural, slight angle and the forearms were horizontal, symmetrical and parallel to each other (Figure 20, pos. U). The right forearm was placed on the input device, and the left forearm on an armrest of similar dimensions. The subjects were told to keep their neck, shoulders, arms and hands as relaxed as possible. The knees were at a right angle and the thighs horizontal.

The input device was framed in a wooden board (54 x 25cm) on which the handball was placed (Figure 21). The eight rigid keys had a surface of 12 x 12mm (key height 6mm, travel < 0.5mm at an applied force of 2N, resonance frequency 432 Hz, damping Q = 17.3). Only one of the keys was used for tapping. A rigid key was chosen to ensure that the tapping characteristics were not affected by key movement and pressure point. The key force was measured with a strain gauge. The handball, thumb and tips of the other fingers were placed on the board. The fingers were slightly bent and only the tip of the index finger was touching the key.

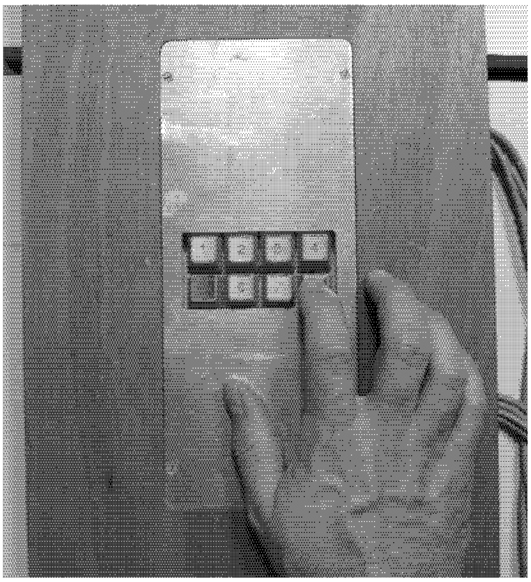


Figure 21 Numeric input device with rigid keys and built-in strain gauge

6.2.2 Tasks

Task 1 ('different postures and tapping rates'):

The first block consisted of a series of short term tasks. The subjects had to tap at 7 rates in a randomised sequence. The rates were 2 Hz, 3 Hz, 4 Hz, 5 Hz, 6 Hz, MAX and OPT and were presented continually by acoustic 'clicks' (with exception of the MAX and OPT conditions). The MAX rate was the maximum possible individual tapping rate that the subject could exert during the registration period. The OPT condition was the tapping rate that the subject esteemed most comfortable. For each condition, the subjects were given about 3 seconds for synchronisation with the metronome (or to find the optimal/maximum rate in the respective conditions). Once synchronised, the recording started for 5 seconds. Between the trials were rests of about 20 seconds. The subjects were told to complete the tasks in their 'natural manner' (which affected mainly the degree of finger bending and vertical movement) and got no feedback of performance.

Next, the subjects repeated the same tapping sequence while assuming posture R, and last while in posture F (Figure 20). In pos. R (slightly reclined), the subjects leaned comfortably against the back support with extended hip and legs. In pos. F (leaning forward) they were leaning on their forearms, assuming a posture that is often adopted by individuals during attention-demanding tasks. The incline of the backrest was not altered in all three postures.

Task 2 ('tapping until exhaustion')

For the last task ('tapping until exhaustion') the subjects assumed again pos. U. This time the subjects had to tap at a given rate of 5 Hz until exhaustion; however after 8 minutes, if they were still tapping, the trial was stopped.

6.2.3 EMG and key force recordings

S-EMG was recorded from the extensor digitorum communis (EXT), flexor digitorum superficialis (FLE), biceps brachii (BIC), triceps brachii (TRI), trapezius pars descendens (TRD) and pars transversa (TRT). MVE (EMG during maximum voluntary contraction) and EMG during relaxation were assessed at the beginning and at the end of the experiments. To determine MVE, the muscles were maximally contracted one after the other. For relaxation EMG, the whole body was relaxed as completely as possible and the EMG was recorded from all six sites simultaneously. For details see 5.1.

Amplifier 1 was used to process the signals of the EXT, FLE, TRD and TRT; amplifier 2 for those of the BIC and TRI. The key force was amplified with a separate strain gauge amplifier. All signals including the key force and that of the frequency generator producing the acoustic 'click' were recorded with programme written in LabView™.

6.2.4 Analysis

The 5th, 50th and 95th percentiles (P5, P50, P95) were computed from the standardised and root mean squared EMG signal as measures for static, medium and dynamic activity. An algorithm was written in Origin™ 5.0 to identify the peaks in the key pressure signal, using the differentiated signal. Manual correction was applied for missed peaks. The mean keystroke interval *k* was calculated from this distribution and used as the lag in the auto-correlation computations (see below). The standard deviation of the inter-keystroke interval was used as a measure for the tapping steadiness. From the key force recordings, the mean peak force of all keystrokes of a trial was determined.

The auto-correlation is a function often used in signal processing for analysing functions or series of values, such as time domain signals. It is the cross-correlation of a signal with itself. Auto-correlation is useful for finding repeating patterns in a signal, such as determining the presence of a periodic signal which has been buried under noise, or identifying the fundamental frequency of a signal which doesn't actually contain that frequency component, but implies it with many harmonic frequencies.

The continuous auto-correlation $r(\tau)$ at lag τ is defined as:

$$r(\tau) = \int_{-\infty}^{\infty} f(t) f(t+\tau) dt$$

The discreet, 1-normed auto-correlation r_k at lag k of a series of measurements y_1, y_2, …, y_N at time t_1, t_2, …, t_N is

$$r_k = \frac{\sum_{i=1}^{N-k} (y_i - \bar{y})(y_{i+k} - \bar{y})}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \qquad (-1 \le r_k \le 1)$$

We are using the auto-correlation function to find the tapping-synchronous component in the (root mean squared) EMG of the investigated muscles. For this, r_k is computed at a lag k equal to exactly one median tapping (keystroke) interval. Interested only in the absolute value $|r_k|$, we expect values between 0 and 1, with $|r_k| = 0$ if there is no tapping-synchronous component at all, and $|r_k| = 1$ if the EMG has exactly the same frequency as the tapping, and the tapping was absolutely regular. $|r_k|$ does not state anything about the time shift between keystroke and EMG (phase).

For the statistical analysis the parameter values were tested for dependence on the given tapping rate with ANOVA for repeated measurements. Greenhouse-Geiser correction (Wiener) was applied. Auto-correlation values were z-transformed as described by R.A. Fisher (Ciba-Geigy, 1980):

$$z = \frac{1}{2} \ln \frac{1+r}{1-r}$$

For the ‘tapping until exhaustion’ task the above parameters were computed on segments of 5s duration. For a smooth graphical representation a 5s window was moved over the time axis with a 1s interval. For numeric analysis, the means of the first 20 s were compared with the means of the last 20 s using the paired Student’s t-test. With Spearman rank correlation (5% significance level) the parameters were compared to the tapping duration.

6.3 Results

6.3.1 MVC and Relaxation

The maximum voluntary contraction measurements before and after the experiments are comparable and do not show any trend (Table 3); the coefficient of variation was in the range between 7 and 14% for the specific muscles.

Table 3 MVC/MVE: EMG during maximum voluntary contractions (MVC) before and after experiments (non standardised RMS values in Volt). Mean ± SD of 9 subjects. Amplifier sensitivity 100 μV/V.

	EXT	FLE	TRI	BIC	TRT	TRD
before	2.5 ± 0.8	1.6 ± 1.1	3.8 ± 2.1	3.5 ± 2.0	2.7 ± 1.5	3.8 ± 1.8
after	2.2 ± 0.6	1.7 ± 1.1	4.1 ± 2.1	3.4 ± 1.8	2.5 ± 1.3	3.9 ± 1.7

Table 4 Relaxation: P5 (static activity) and P50 (median activity) of relaxation EMG. Mean ± SD of 9 subjects in %MVE

		EXT	FLE	TRI	BIC	TRT	TRD
P5	**before**	0.8 ± 0.5	1.3 ± 1.0	0.4 ± 0.3	0.5 ± 0.3	1.8 ± 0.9	0.9 ± 0.5
	after	0.7 ± 0.5	1.2 ± 1.1	0.7 ± 0.8	0.5 ± 0.3	2.4 ± 2.2	1.4 ± 1.4
P50	**before**	1.4 ± 1.0	2.3 ± 2.5	0.5 ± 0.4	0.6 ± 0.4	2.6 ± 1.3	1.3 ± 0.8
	after	1.0 ± 0.7	2.3 ± 3.0	1.0 ± 1.2	0.6 ± 0.4	3.6 ± 3.2	2.4 ± 2.6

Inspection of the EMG graphs during relaxation revealed different sorts of residual activity and noise: Two subjects showed a pattern with a rate of about 10 Hz that originated probably from a single MU firing (Figure 22a). In some trapezius (and once in the triceps) recordings of one specific subject (subj. 8) a periodic artefact appeared at a rate of about 1 Hz, which originated probably from heart beat (Figure 22b). Some subjects were unable to achieve good relaxation (Figure 22c). High noise levels as in Figure 22d were seen rarely; mostly, noise was lower than the residual activity and not stable. A realistic baseline could therefore not be determined to be subtracted during the EMG standardisation.

The P5 and P50 (static and median activity) of the relaxation EMG recordings before and after the experiments are comparable and do not show any trend (Table 4); P50 was used because P95 was sometimes interfered by the heart beat.

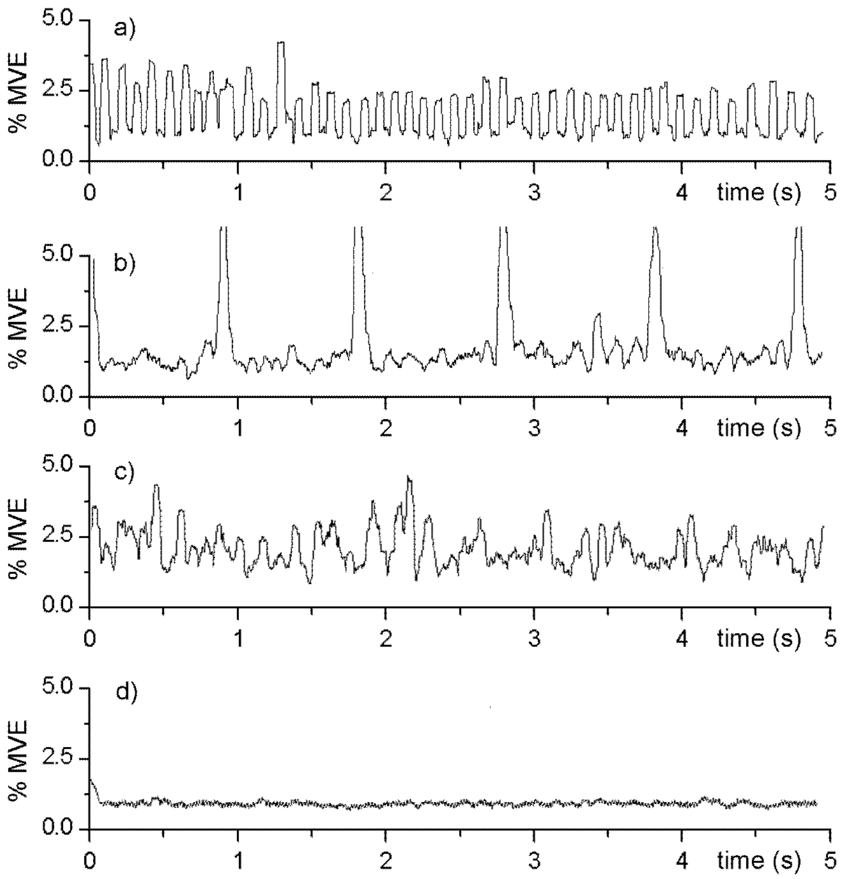


Figure 22 Examples of residual EMG during relaxation. a) 10 Hz pattern, probably from a single MU firing (finger extensor, subj. 2, before exp.). b) 1 Hz pattern, probably from heart beat (plus residual activity) (trapezius p. desc., subj. 8, after exp.). c) noise (biceps, subj. 9, after exp.). d) incomplete relaxation (trapezius p. desc., subj. 1, after exp.).

6.3.2 Performance task 1 ('different postures and tapping rates')

The tapping rate had a significant and high effect on tapping steadiness, expressed by the standard deviation of the inter-keystroke interval ($F_{TapRate}$ = 12.0***). Faster tapping resulted in higher precision (Figure 23). The posture had no influence (F_{Pos} = 1.7). The significant interaction term $F_{TapRate*Pos}$ = 3.2* was caused by a high SD at pos. F/3Hz.

Expressing the steadiness by the coefficient of variation CV (CV=SD/mean * 100%), about half of the subjects were tapping less regularly at medium rates (3 and 4 Hz) and more regularly at slow, fast, optimal and maximum rates (example in Figure 24). Other subjects however had similar CV's throughout all tapping rates and postures.

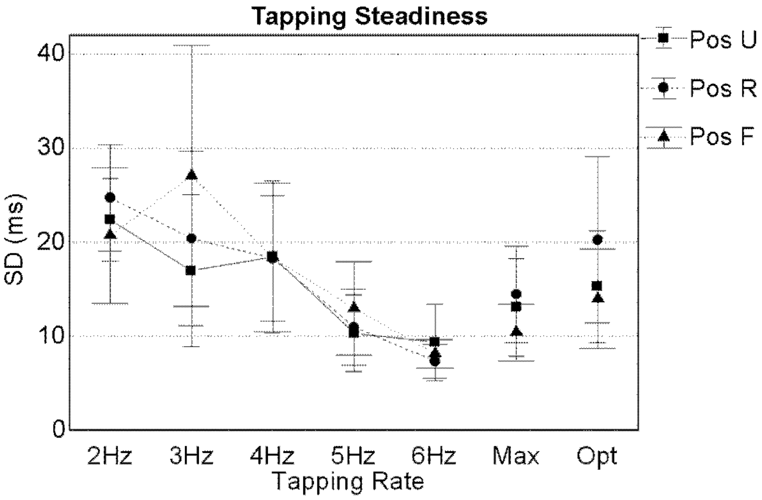


Figure 23 Tapping steadiness (mean ± SD of 9 subjects), expressed by the standard deviation of the inter-keystroke interval, at posture U (upright), R (slightly reclined) and F (leaning forward). For measured tapping rates at Max and Opt see Table 5).

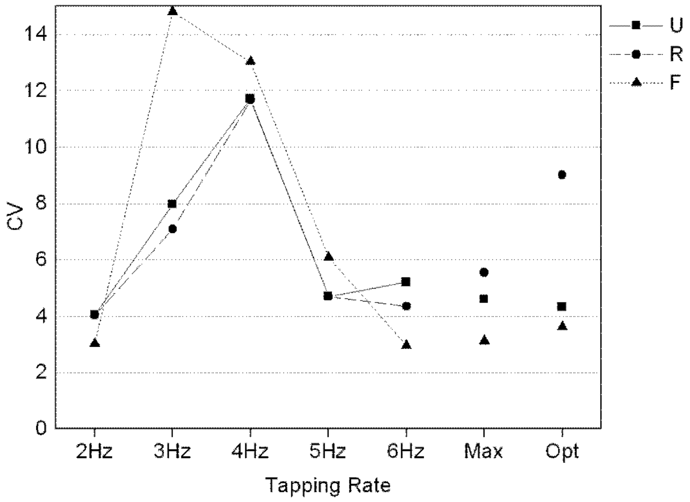


Figure 24 Tapping steadiness of subj. 4, expressed by the coefficient of variation (CV) of the inter-keystroke intervals (in %), at posture U (upright), R (slightly reclined) and F (leaning forward). Measured tapping rate at Max: 6.2, 6.0 and 6.1 Hz (for pos. U, R and F, resp.); at Opt: 3.3, 3.0 and 3.2 Hz (for pos. U, R and F, resp.)

Table 5 Measured tapping rates of the Opt and Max conditions (mean ± SD of period and frequency range)

Tapping rate	Position	Period	Frequency range
Opt	Pos. U	302 ± 65 ms	2.3...5.3 Hz
	Pos. R	336 ± 94 ms	2.0...5.5 Hz
	Pos. F	309 ± 89 ms	2.2...5.3 Hz
Max	Pos. U	162 ± 16 ms	5.5...8.2 Hz
	Pos. R	167 ± 23 ms	5.0...8.0 Hz
	Pos. F	165 ± 22 ms	5.1...8.4 Hz

While the effect of the tapping rate on the finger force peaks was not significant ($F_{TapRate} = 2.0$), the effect of body posture was ($F_{Pos} = 5.2$*, $F_{TapRate*Pos} = 2.7$). The highest finger force was usually achieved when leaning forward (Figure 25)

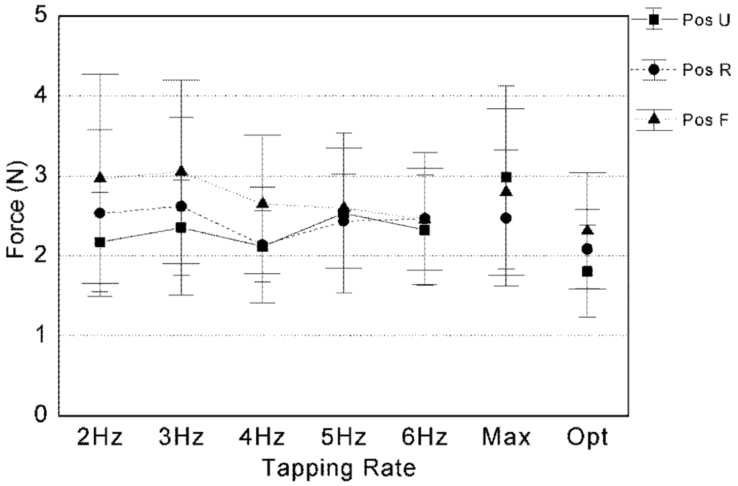


Figure 25 Mean finger peak forces (from mean individual values), at posture U (upright), R (slightly reclined) and F (leaning forward)

6.3.3 EMG task 1 ('different postures and tapping rates')

Table 6 Dependence of static (P5) / dynamic (P95) activity and $|r_k|$ on posture and tapping rate; F-values and significances

		EXT	**FLE**	**TRI**	**BIC**	**TRT**	**TRD**
P5	F_{Pos}	**10.5 ****	0.2	**5.5 ***	**4.8 ***	**9.5 ****	3.2
	F_{Tapp}	**29.0 *****	**33.9 *****	**10.7 ****	**15.4 *****	**7.6 ****	**9.2 *****
	$F_{Pos*Tapp}$	**2.9 ***	0.7	2.0	2.1	0.8	0.5
P95	F_{Pos}	**5.6 ***	1.6	**5.6 ***	**4.4 ***	**5.6 ***	3.0
	F_{Tapp}	**10.9 ****	**29.9 *****	**12.7 ****	**20.1 *****	**7.8 ***	**7.5 ****
	$F_{Pos*Tapp}$	0.8	1.4	**3.5 ***	2.8	0.6	0.4
$\|r_k\|$	F_{Pos}	1.4	0.7	0.7	0.2	1.5	1.8
	F_{Tapp}	**5.3 ****	**12.7 *****	**15.3 *****	**13.9 *****	1.1	2.4
	$F_{Pos*Tapp}$	0.9	1.0	0.6	1.0	0.6	1.0

* $0.01 \le p < 0.05$
** $0.001 \le p < 0.01$
*** $p < 0.001$

Table 7 Auto-correlation values $|r_k|$ (main ± SD) for main tapping rates at upright position

	EXT	FLE	TRI	BIC	TRT	TRD
2 Hz	0.6 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	0.1 ± 0.1
4 Hz	0.7 ± 0.1	0.4 ± 0.2	0.1 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.2
6 Hz	0.8 ± 0.1	0.7 ± 0.1	0.4 ± 0.2	0.2 ± 0.2	0.0 ± 0.2	0.0 ± 0.1
MAX	0.7 ± 0.1	0.6 ± 0.1	0.4 ± 0.2	0.3 ± 0.1	0.1 ± 0.2	0.1 ± 0.1
OPT	0.7 ± 0.1	0.3 ± 0.2	0.0 ± 0.1	0.0 ± 0.2	0.0 ± 0.1	0.0 ± 0.1

Finger extensor EMG in task 1

Dependence of P5/P95 on posture: The static and dynamic activity of the finger extensor depended significantly on the posture (Figure 27, Table 6). They were significantly reduced in pos. R and increased in pos. F.

Dependence of P5/P95 on tapping rate (upright posture): The static and dynamic activity of the finger extensor depended significantly on the tapping rate. Static activity was below 5% in all subjects and tapping rates. With slow tapping (up to about 4 Hz), subjects had similar static, but varying median (2 - 20%) and dynamic (5 - 40%) activities (see example at 3 Hz, Figure 26 left). With fast tapping the differences between the subjects in EMG activity were equalized (example at 6 Hz, Figure 26 right).

Dependence of $|r_k|$ on posture: The auto-correlation values of the finger extensor did not depend on the posture.

Dependence of $|r_k|$ on tapping rate (upright posture): The auto-correlation values of the finger extensor depended significantly on the tapping rate. They were between 0.6 at slow tapping and 0.8 at 6 Hz tapping.

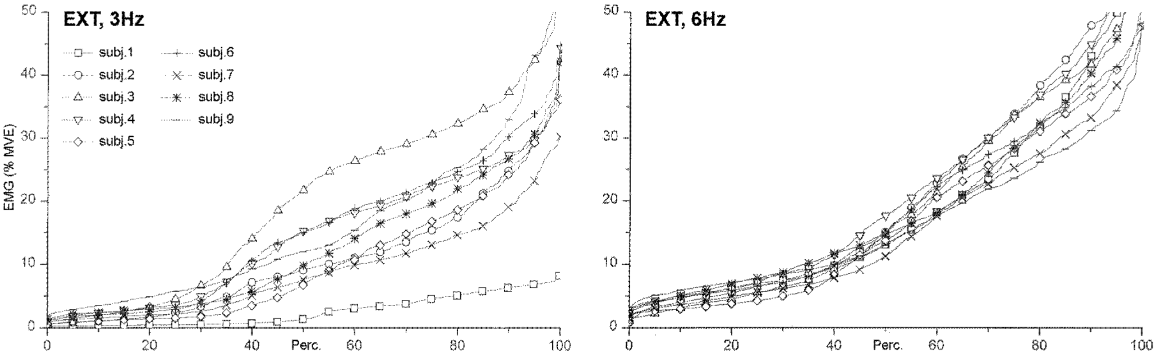
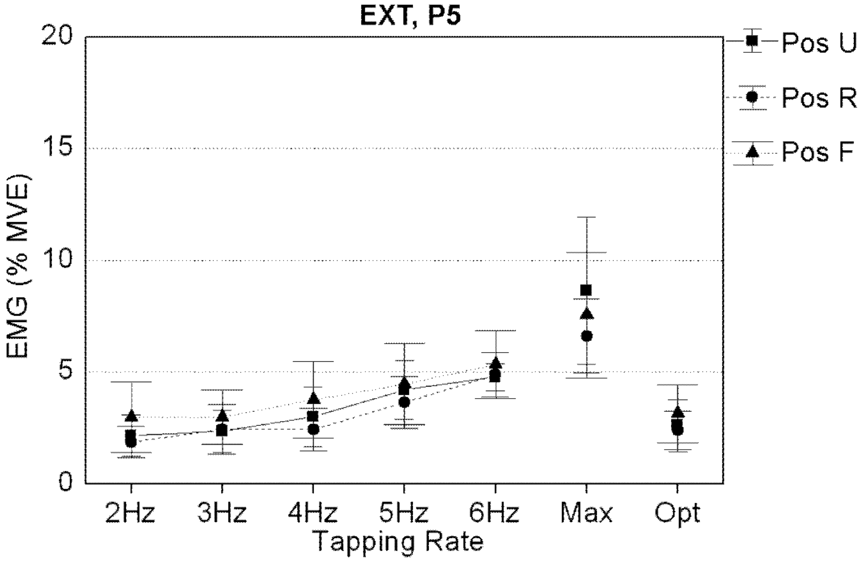
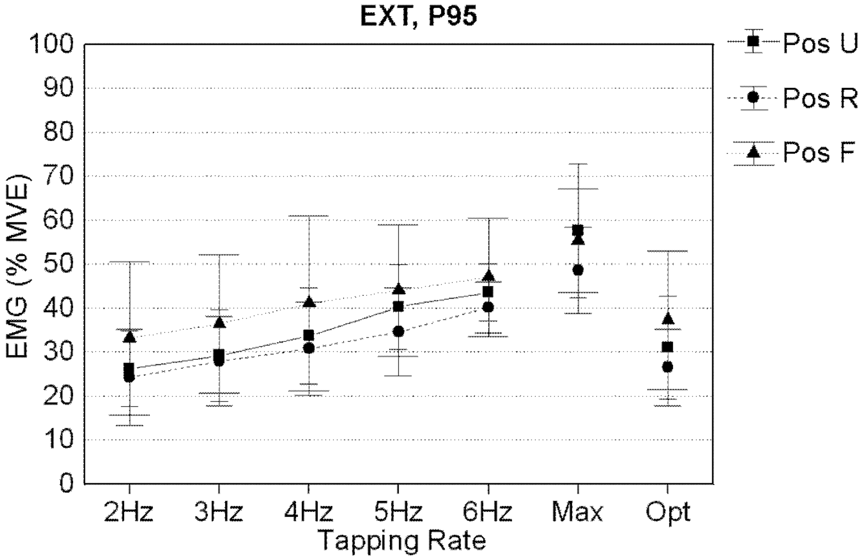


Figure 26 Examples of finger extensor EMG (all percentiles) at 3 Hz and 6 Hz (upright posture)



$F_{Pos} = 10.5$ ** $F_{Tapp} = 29.0$ ***



$F_{Pos} = 5.6$ * $F_{Tapp} = 10.9$ **

Figure 27 Static (P5) and dynamic (P95) activity of the finger extensor at posture U (upright), R (slightly reclined) and F (leaning forward)

Finger flexor EMG in task 1

Dependence of P5/P95 on posture: The static and dynamic activity of the finger flexor did not depend on the posture (Figure 29, Table 6).

Dependence of P5/P95 on tapping rate (upright posture): The static and dynamic activity of the finger flexor depended significantly on the tapping rate. With slow and OPT tapping subjects usually had low static and median contractions (up to about the 80th percentile) (see example at 2 Hz, Figure 28 left). About half of the subjects didn't have dynamic activity either, which means that their slow tapping was achieved only with extensor activity. Subject 4 released the flexor only during very short periods. His EXT activity was relatively high too, so that his finger antagonism was probably concurrent and not co-operative. With increasing tapping rate, a gradual rise of flexor activity set in with individual variation of intensity. The static activity stayed around 2% MVE in most subjects. Only at MAX (shown in Figure 28 right) some subjects were no longer able to release the muscle so that static activity increased. Two subjects showed a considerable overall rise of activity during MAX tapping with dynamic values over 100% MVE (up to 180% in subject 4).

Dependence of $|r_k|$ on posture: The auto-correlation values of the finger flexor did not depend on the posture.

Dependence of $|r_k|$ on tapping rate (upright posture): The auto-correlation values of the finger flexor depended significantly on the tapping rate. They were between 0.3 at slow tapping and 0.7 at 6 Hz tapping.

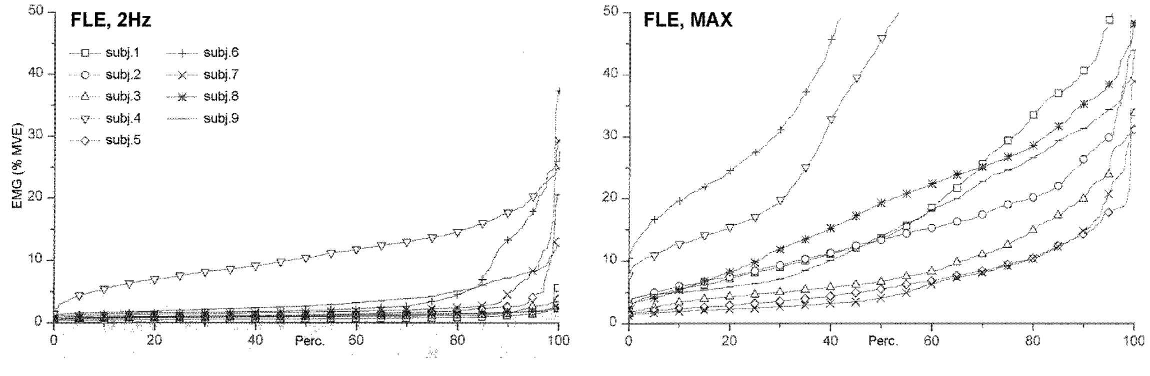
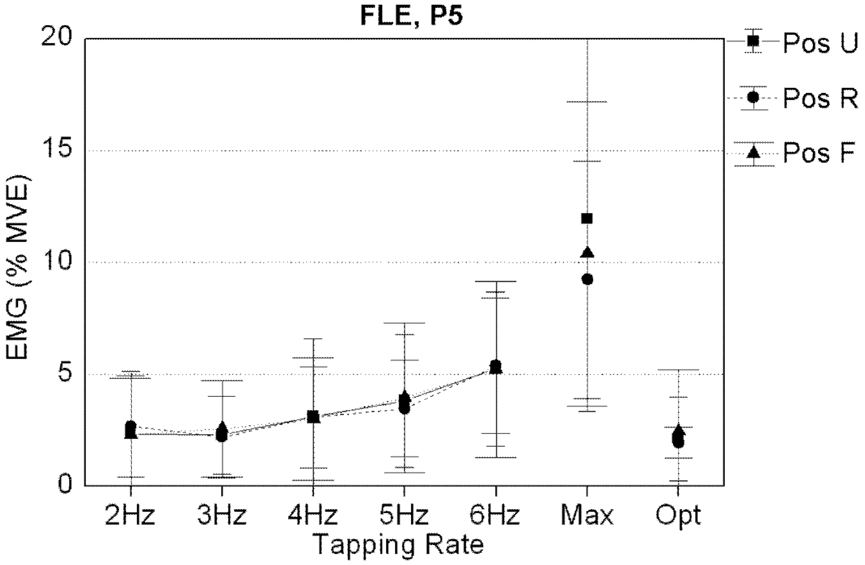
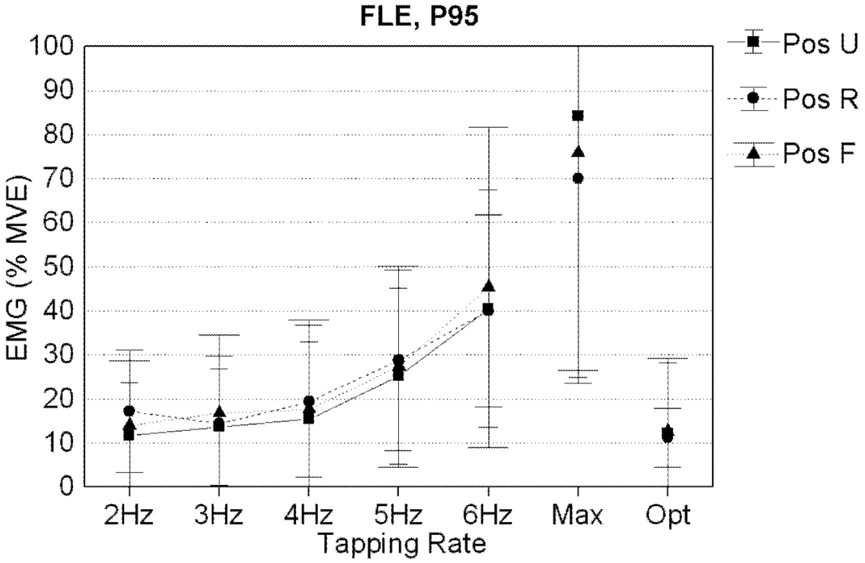


Figure 28 Examples of finger flexor EMG (all percentiles) at 2 Hz and MAX (upright posture)



$F_{Pos} = 0.2$ **$F_{Tapp} = 33.9$ *****



$F_{Pos} = 1.6$ **$F_{Tapp} = 29.9$ *****

Figure 29 Static (P5) and dynamic (P95) activity of the finger flexor at posture U (upright), R (slightly reclined) and F (leaning forward)

Triceps and biceps EMG in task 1

Dependence of P5/P95 on posture: The static and dynamic activity of the triceps and biceps depended significantly on the posture (Table 6; triceps shown in Figure 31). Triceps activity was significantly higher when leaning forward (pos. F) and somewhat higher when slightly reclined (pos. R). Biceps activity increased only slightly when leaning forward.

Dependence of P5/P95 on tapping rate (upright posture): The static and dynamic activity of the triceps and biceps depended significantly on the tapping rate, but were always very low (triceps 6 Hz shown in Figure 30 left). Only at MAX some individuals increased dynamic activity, while others kept it at a low or moderate level (Figure 30 right). The unusual shape of the curve of subject 3 was due to a very high static and dynamic increase in the second half of the task (as seen in the time plot).

Dependence of $|r_k|$ on posture: The auto-correlation values of the triceps and biceps did not depend on the posture.

Dependence of $|r_k|$ on tapping rate (upright posture): The auto-correlation values of the triceps and biceps depended significantly on the tapping rate. The values for the triceps were between 0.1 at slow tapping and 0.4 at fast tapping; synchronicity could be visually confirmed for most subjects. The values for the biceps were around zero at slow tapping and 0.3 at fast tapping; synchronicity could be visually confirmed for half of the subjects.

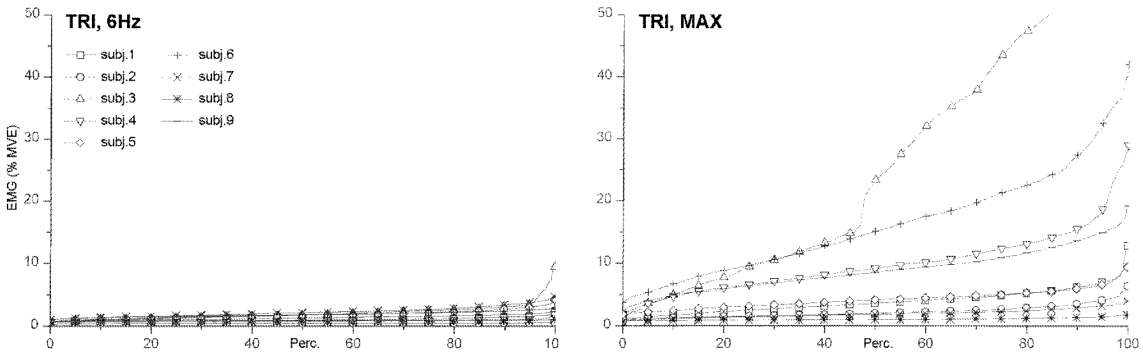
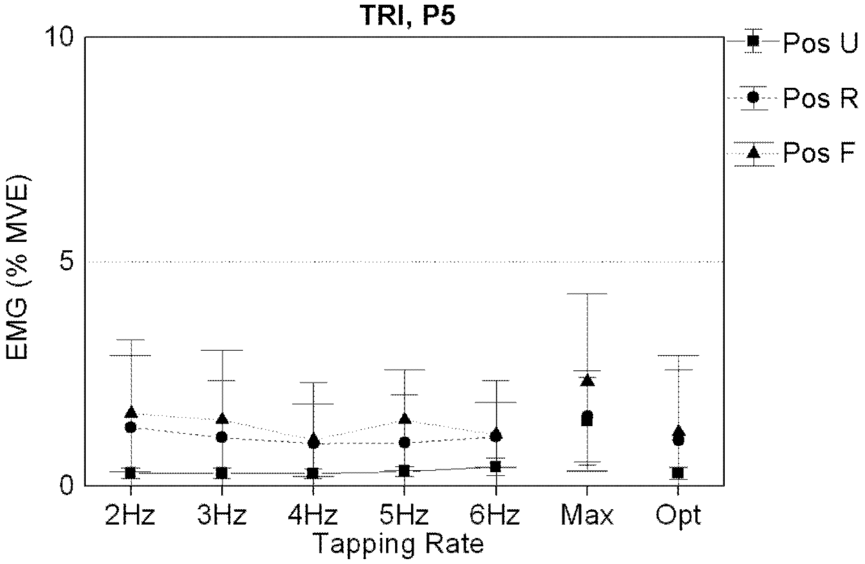
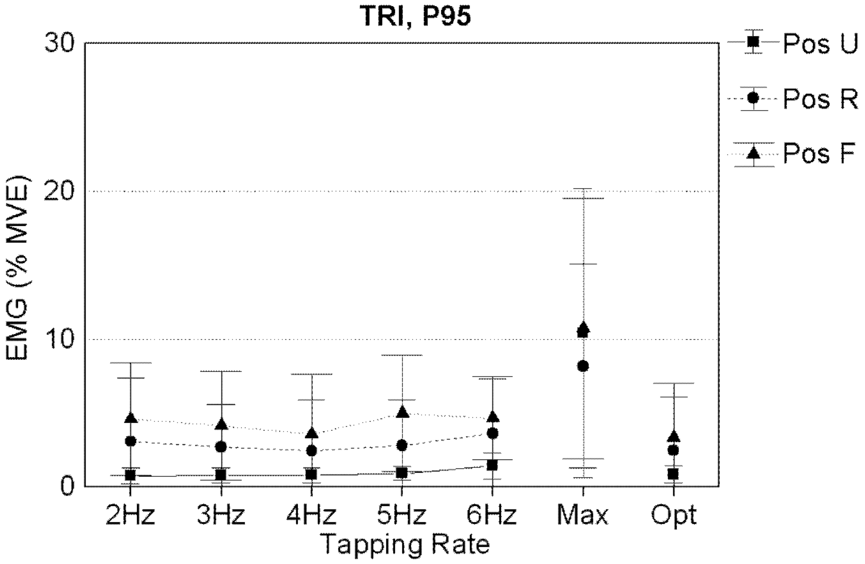


Figure 30 Examples of triceps EMG (all percentiles) at 6 Hz and MAX (upright posture)



F_{Pos} = 5.5 * F_{Tapp} = 10.7 **



F_{Pos} = 5.6 * F_{Tapp} = 12.7 **

Figure 31 Static (P5) and dynamic (P95) activity of the triceps at posture U (upright), R (slightly reclined) and F (leaning forward)

Trapezius pars transversa EMG in task 1

Dependence of P5/P95 on posture: The static and dynamic activity of the trapezius p. transversa depended significantly on the posture (Figure 33, Table 6). An increase was observed when leaning forward (pos. F) and a small decrease when slightly reclined (pos. R).

Dependence of P5/P95 on tapping rate (upright posture): The static and dynamic activity of the trapezius p. transversa depended significantly on the tapping rate. Most activity was low (except at MAX, where only two subjects kept static and dynamic activity low). Only two subjects had considerable activation: Subject 6 had elevated values of a more or less constant magnitude throughout all tapping rates. An example of a change of co-activation within a subject can be seen in subject 9 comparing the 2 Hz and the 3 Hz plots (Figure 32). Her activity was elevated in about half of the tasks and low in the other tasks. The elevated P95 of subject 8, seen at all tapping rates, was caused by heartbeat.

Dependence of $|r_k|$ *on posture:* The auto-correlation values of the trapezius p. transversa did not depend on the posture.

Dependence of $|r_k|$ *on tapping rate (upright posture):* The auto-correlation values of the trapezius p. transversa did not depend on the tapping rate. The values were very low in most subjects, but some individuals showed patterns synchronous with the tapping and values up to 0.4 at fast tapping.

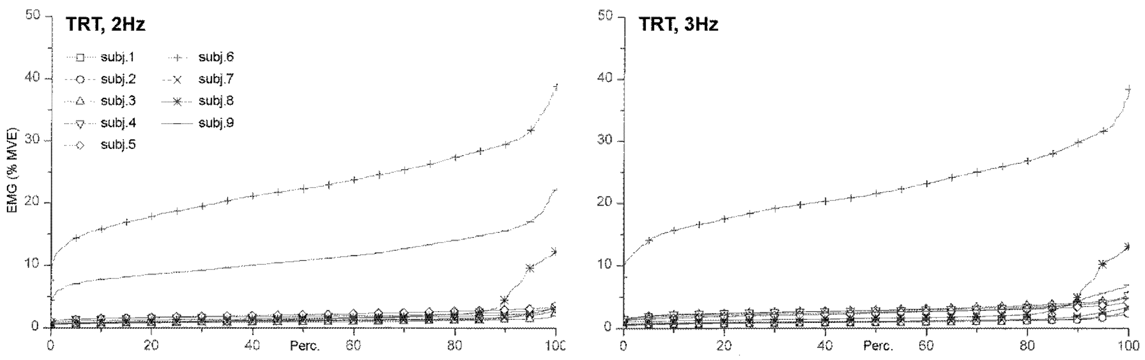
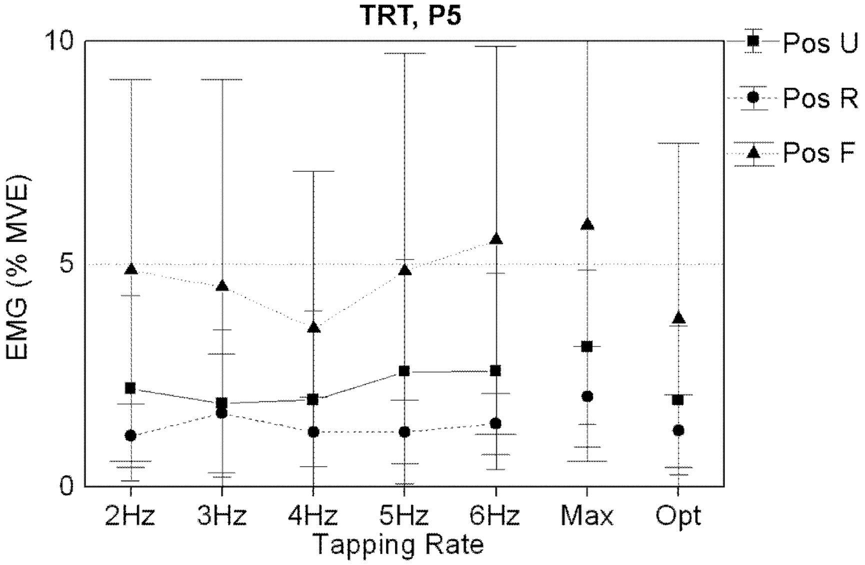
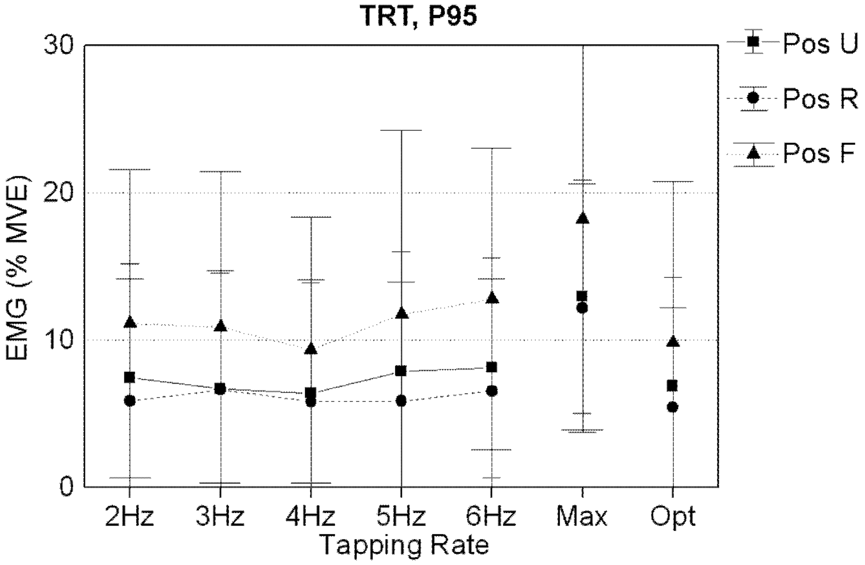


Figure 32 Examples of trapezius p. transversa EMG at 2 Hz and 3 Hz (upright posture)



F_{Pos} = 9.5 ** F_{Tapp} = 7.6 **



F_{Pos} = 5.6 * F_{Tapp} = 7.8 *

Figure 33 Static (P5) and dynamic (P95) activity of the trapezius p. transversa at posture U (upright), R (slightly reclined) and F (leaning forward)

Trapezius pars descendens EMG in task 1

Dependence of P5/P95 on posture: The static and dynamic activity of the trapezius p. descendens did not depend on the posture (Figure 35, Table 6).

*Dependence of P5/P95 on tapping rate (upright posture):*The static and dynamic activity of the trapezius p. descendens depended significantly on the tapping rate. Most individuals had low activities up to about 4 Hz and medium levels at 5 Hz and above (Figure 34). However some subjects activated the muscle considerably and unpredictably, similar to the observations in the trapezius p. transversa.

Dependence of $|r_k|$ *on posture:* The auto-correlation values of the trapezius p. descendens did not depend on the posture.

Dependence of $|r_k|$ *on tapping rate (upright posture):* The auto-correlation values of the trapezius p. descendens did not depend on the tapping rate. Most values were low and no value surpassed 0.35. Tapping-synchronous patterns were observed in about one out of five trials at all tapping rates except the OPT condition.

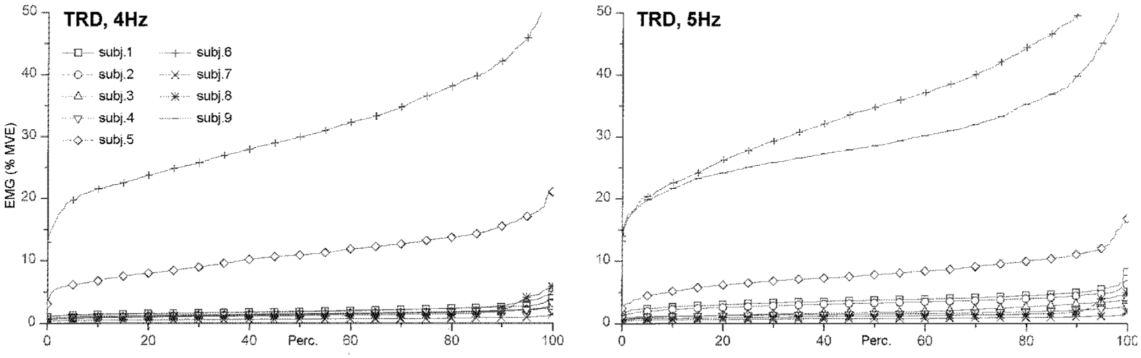
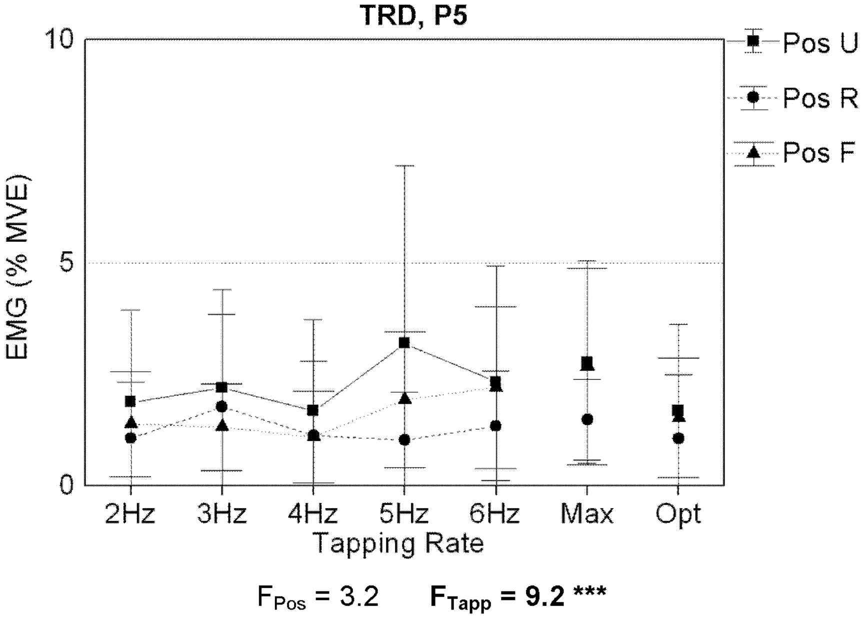
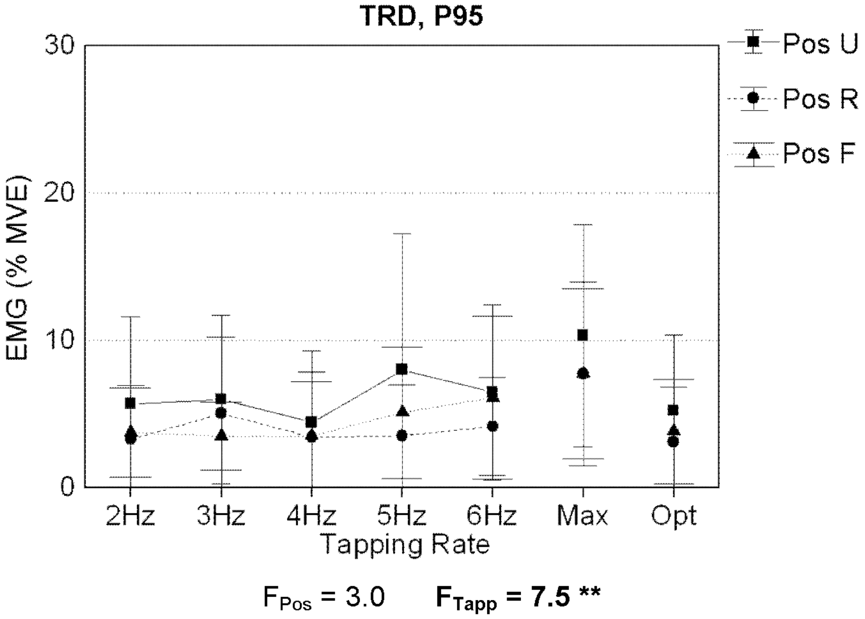


Figure 34 Examples of trapezius p. descendens EMG at 4 Hz and 5 Hz (upright posture)



F_{Pos} = 3.2 **F_{Tapp} = 9.2 *****



F_{Pos} = 3.0 **F_{Tapp} = 7.5 ****

Figure 35 Static (P5) and dynamic (P95) activity of the trapezius p. descendens at posture U (upright), R (slightly reclined) and F (leaning forward)

6.3.4 Performance task 2 ('tapping until exhaustion')

The shortest tapping time until a subject felt exhaustion was about 50 s (subjects 4 and 7) (Figure 36). Two subjects (6 and 8) felt no exhaustion even after 8 minutes, when the trial was stopped.

Only two subjects were able to keep the given tapping rate of 5 Hz more or less exactly, one of which was a subject tapping 8 minutes. The rate of two subjects (6 and 7) was constantly too high. Most subjects started with 5 Hz and slowed down gradually. On average, the tapping rate was diminished by 0.2 ± 0.3 Hz by the end of the trial ($p = 0.05$). None of the different parameters correlated significantly with the time until exhaustion.

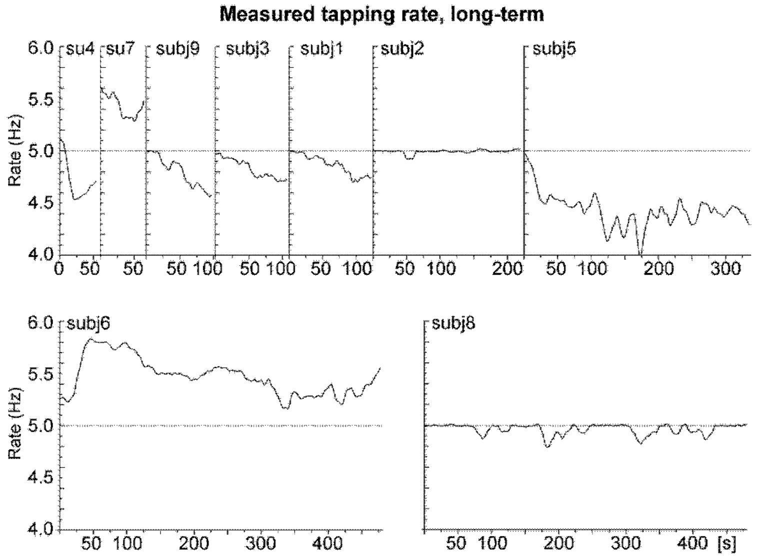


Figure 36 Long term task: Measured tapping rate. Ordered by time until exhaustion.

Table 8 Long term task: P5, P95 and auto-correlation (mean ± SD) at begin and change at end of trial. t-values for significance of change

		EXT	FLE	TRI	BIC	TRT	TRD
P5	**Begin**	4.1±1.4	3.7±2.8	0.6±0.4	0.5±0.3	2.8±2.3	3.0±3.3
	Change	+0.5±1.2	+1.8±1.5	+0.5±0.7	+0.7±1.0	+0.6±1.3	-0.5±1.0
	t	1.4	**3.3***	1.5	2.0	1.6	-1.1
P95	**Begin**	38.6±10.7	24.8±17.7	1.9±1.5	1.1±0.8	9.0±7.1	7.7±7.4
	Change	+0.1±10.5	+15.2±16.6	+3.9±5.9	+2.7±3.6	+3.5±3.6	+1.5±2.1
	t	0.1	**2.6***	1.9	2.0	**2.8***	2.2
$\lvert r_k \rvert$	**Begin**	0.7±0.2	0.7±0.2	0.3±0.3	0.2±0.2	0.1±0.1	0.1±0.1
	Change	-0.1±0.1	+0.1±0.1	+0.2±0.3	0.0±0.2	0.0±0.1	+0.1±0.1
	t	**-2.6***	1.8	2.2	0.3	1.2	1.4

6.3.5 EMG task 2 ('tapping until exhaustion')

Finger extensor and flexor

With few exceptions, most finger extensor activities remained at a steady level (Table 8, Figure 37). The finger flexor activities however increased significantly (both static and dynamic; Figure 38). Only subject 2 kept a very low flexor activity throughout 200 s. Very high increases of dynamic flexor activity was observed in subjects 1 and 9 (together with a considerable extensor dynamic increase).

Auto-correlation values decreased significantly in the extensor.

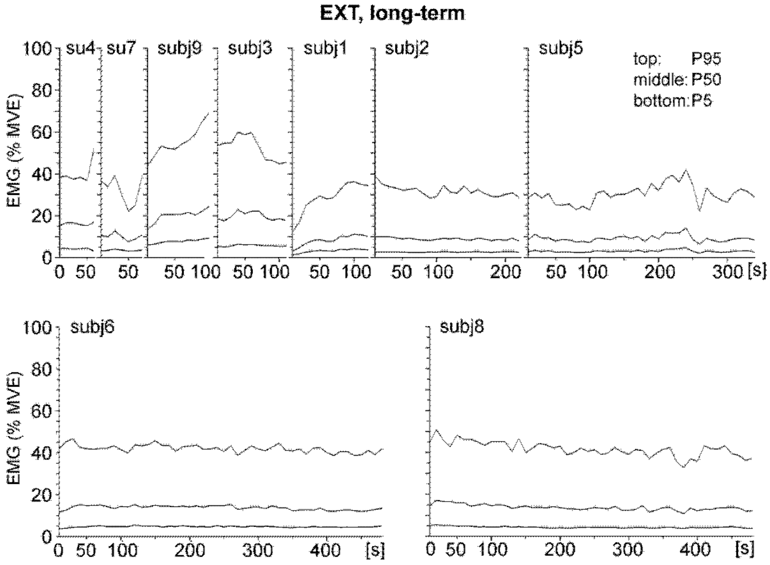


Figure 37 Long term task: Activity of finger extensor. Ordered by time until exhaustion. $|r_k|$ decreased significantly.

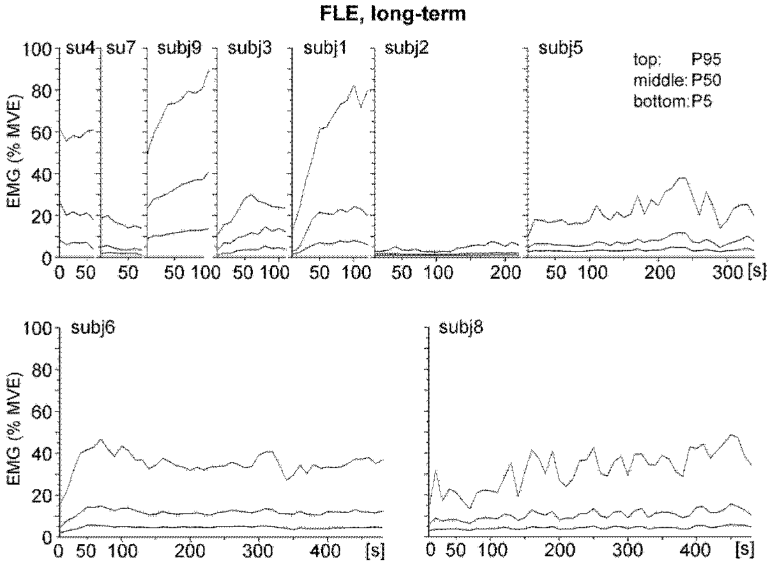


Figure 38 Long term task: Activity of finger flexor. Ordered by time until exhaustion. P5 and P95 increased significantly.

Biceps and triceps

Biceps and triceps activities increased and decreased simultaneously and had mostly comparable levels (Table 8, Figure 39, Figure 40). Significant changes of EMG activity or auto-correlation levels were not seen. In four subjects (2, 4, 7 and 8) the activities remained at a more or less constant and relatively low level. In three subjects (1, 5 and 6) they increased slightly, and in subject 9 they increased to a medium level. Subject 3 started with low levels and increased activity by more than 2000%. However before stopping, the levels turned back to about 1000% of the original values.

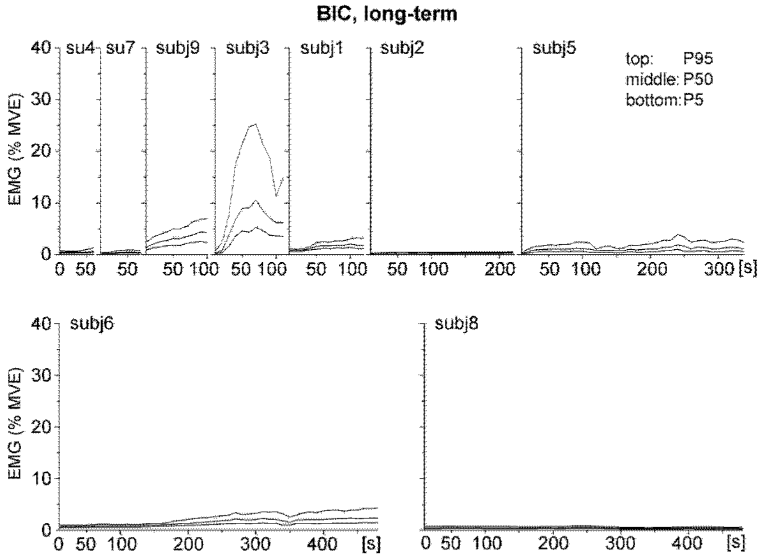


Figure 39 Long term task: Activity of biceps. Ordered by time until exhaustion.

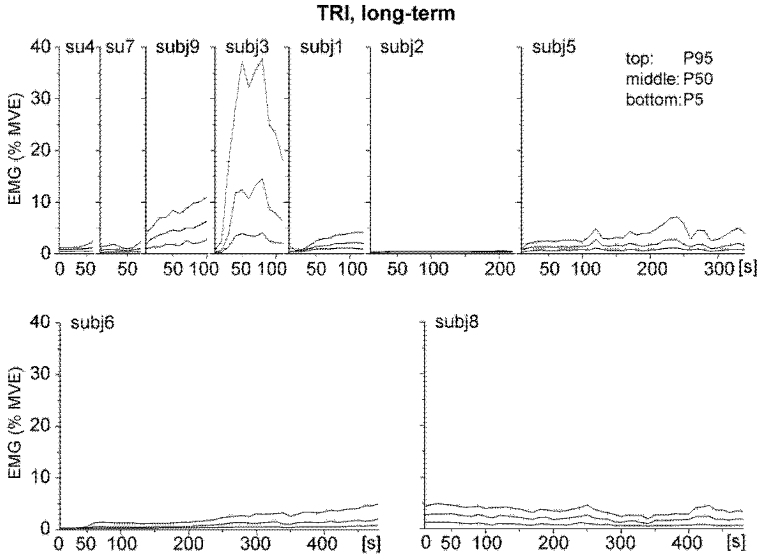


Figure 40 Long term task: Activity of triceps. Ordered by time until exhaustion.

Trapezius pars transversa and pars descendens

In the trapezius, five subjects had similar and four had higher P5 and P95 levels than in the short-term task (Table 8, Figure 41, Figure 42). The trapezius p. transversa showed a significant increase in dynamic activity. A part of the subjects (2, 7 and 8) had constantly low activities (the high dynamic activity of subject 8 was caused by heart beat). Subject 5 switched from low to medium activity after 200 s. Subject 3's high upper arm increase had some correspondence in the trapezius. Subject 1 had a sudden increase only in the transversal part of the trapezius. Two subjects (6 and 9) had high initial values and increasing dynamic but decreasing static activities. It was the same two subjects that had the highest activity levels also in the short term task.

Auto-correlation levels did not change significantly.

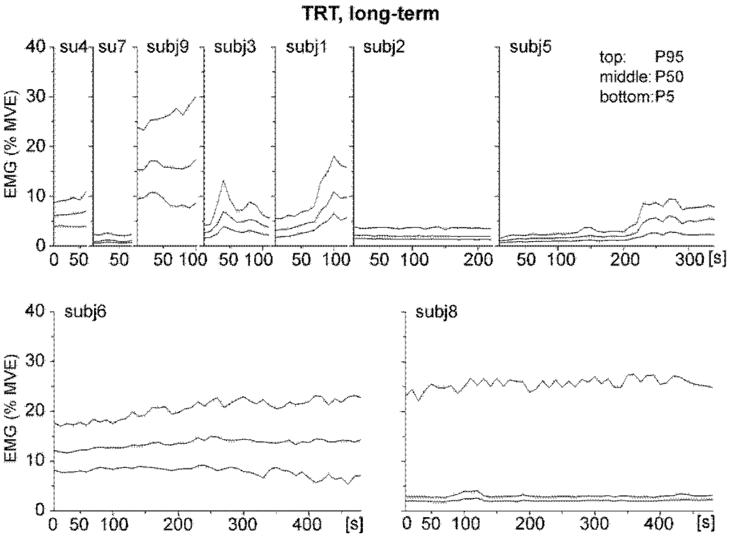


Figure 41 Long term task: Activity of the trapezius p. transversa. Ordered by time until exhaustion. P95 increased significantly.

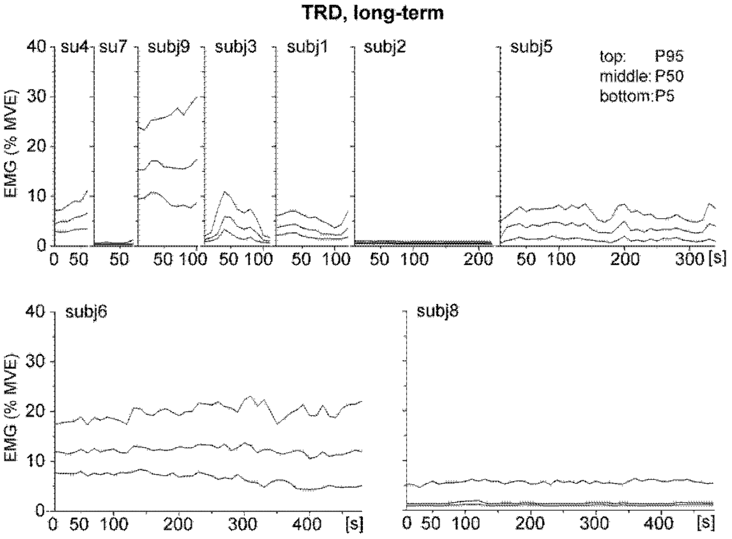


Figure 42 Long term task: Activity of the trapezius p. descendens. Ordered by time until exhaustion.

6.4 Discussion

6.4.1 Methods

EMG at rest: Visual control of the EMG at rest confirmed that it originated mostly from residual muscle activity and not from noise. The instability of residual activity and noise made it difficult to determine a realistic baseline to be subtracted during the EMG standardisation; however as the noise seems not to have affected the results with more than 1% MVE, this decision should be justified.

MVC and MVE: MVC/MVE measurements were made at maximum *static* muscle contraction, maintaining the contraction during several seconds. The RMS averaging with a moving window of 1s smoothed all peaks. All other EMG signals were RMS-averaged with a 50 ms window. This explains why the P95 in dynamic contractions occasionally surpassed 100% (static) MVE, as observed in the finger muscles. The P95 parameter should thus be read with care, as it refers to a static contraction. For the P5 however, as a measure of the static activity, %MVE should be a physiologically meaningful notation.

Tapping steadiness: The standard deviation (SD) of the inter-keystroke interval will likely decrease as the inter-keystroke interval decreases. A coefficient of variation (CV) (dividing the SD by the mean) would remove this effect, but cannot be justified by a valid model. A CV of 4% in a 2 Hz tapping, e.g., means a 20 ms SD. The same CV in a 1 Hz tapping means a SD of 40 ms – however there’s no reason why in the slower tapping the nervous system should work only half as precisely. An example with a CV was nevertheless depicted in Figure 24 to illustrate the instability between 3 and 4 Hz seen in some subjects.

6.4.2 Task 1 (‘different postures and tapping rates’)

Finger muscles: At slow tapping, finger flexion was generally driven by gravity, and most subjects used only the finger extensor and barely the flexor. The increase of the flexor activity at the very right of the percentile curves (Figure 28, left) of some subjects shows their sudden finger flexion just during a few ms before hitting the key. The differences of the extensor EMG in the median and high percentile ranges (Figure 26, left) is presumably due to different neuromotor strategies, either lifting the finger immediately after a click or keeping it on the key for a while.

At fast tapping, the flexor was involved more. It had to overcome inertia and the elasticity of the finger’s spring-mass system, but also the rising static extensor contractions. Extensor dynamic activities on the other side did not increase on average but were equalized to similar levels in all subjects, as there was no spare time to rest the finger on the key (Figure 26, right). This confirms the change from a co-operative to a competitive antagonism found by Weiss (1999) when switching from slow to fast tapping.

The auto-correlation values of the finger extensor (mean values 0.6 at slow and 0.8 at fast tapping) can be seen as reference that the other muscles, which are not primarily involved in the tapping, cannot exceed.

Upper arm muscles: In both upper arm muscles the activity was mostly low (except at MAX in certain subjects). Auto-correlation values of 0.4 in the triceps of some subjects at fast tapping demonstrate that a certain synchronicity with the tapping was given. The EMG levels were too low to interpret the activity as stabilising or preparatory activity, particularly as there was no mechanical need. A preparatory activation should trigger higher forces.

Trapezius muscle: In a large part of the subjects and conditions some activity was always present in both parts of the trapezius muscle, often even during relaxation, but did rarely surpass 5% MVE. Some subjects had near-zero static activity. Some other subjects had highly elevated values (such as 20% MVE of static activity in the p. descendens) throughout all conditions. Some subjects activated the trapezius unsystematically (as in Figure 32). These cases support the assumption that there is no need for trapezius activation for the given task and setting, but that sometimes unnecessary activity is developed. The included subjects did not suffer from WRMD at present. A prospective study could clarify if subjects with intermittent or regular trapezius co-activity are going to develop WRMD.

The activity of the transversal part of the trapezius muscle was highly increased in pos. F as a consequence of the shoulder blades being shoved backwards. In the slightly reclined position there was a trend towards lower activity.

Only in some cases auto-correlations indicated a synchronisation of trapezius activity with finger tapping (presumably as a result of a reduced, unsuppressed co-innervation). Often the high trapezius activity and the tapping had different frequencies and could be explained as inherent to the motor programme or as reflexes for head stabilisation and respiration compensation.

Tapping steadiness: A linear trend could be observed in tapping steadiness between 2 and 6 Hz with the most steady performance at 6 Hz with an outlier at 3Hz/Pos.F. Fast tapping has a rhythmic character and the synchronisation with the acoustic click does not occur with every single beat, whereas slow tapping is more target-oriented. The motor programmes must therefore be different. As seen before, the finger flexor is little involved with slow tapping, so the target hitting occurs mainly by a relaxation of the extensor and the aid of gravity. With fast tapping the flexor does the target hitting, and it is doing this during the contractile phase which increases the precision of the target hitting. The unstable performance of some subjects at medium tapping rates could be explained by the fact that in this range they may be using, alternatingly or concurrently, both the 'targeted' and the 'rhythmic' motor programme.

Laursen et al (1998) described a decrease in precision following an increase in the speed demand at which a *targeted* task had to be carried out. Both higher speed and higher precision demands led to an increase in shoulder muscle EMG.

6.4.3 Task 2 ('tapping until exhaustion')

Performance: Although the time until exhaustion varied from 50 s to eight minutes, clear predictors for exhaustion could not be found in the different parameters. With only nine subjects and a significance level of 5%, small effects could not be evaluated, since Spearman rank correlation analysis became significant only with stronger associations. Sensation of fatigue in the acting muscles seemed not to be decisive. Probably motivation and general fatigue played a major role in the decision of an individual to stop the experiment.

Finger muscles: Some subjects kept steady levels while others increased finger extensor and especially flexor activity. Presumably the coordination between the two muscles decreased with progressing exhaustion, resulting in more competitive antagonism and activation of both muscles.

Upper arms: The activities started at low levels. While some subjects kept a low level, others increased their contraction during the task (subject 3 up to 40% MVE in the triceps P95). Biceps and triceps activity increased at the same time and the contractions were isometric (the subjects apparently did not press their forearm against the desk or lift it). The increase was completely unnecessary from a biomechanical, stabilising or work organisational point of view.

Trapezius: Individual differences were large. Static activity was more or less constant in most subjects. Fatigue did apparently not cause neck tension, caused by increased tonic muscle activity, as expected. Dynamic activity increased slightly, but significantly in the transversal part. Keller and Strasser (1996) had similar findings with text entry during 10 minutes, where an increase of mean trapezius EMG was seen from 3 to 5% MVE with, and from 7 to 10% without supported elbows.

6.4.4 Conclusions

The main finding of this study is that in a laboratory setting with *high finger activity* and *low attention demand* the level of activity of the upper arm and trapezius muscles is considerably elevated in some – but not all – subjects, especially when tapping at high rates and leaning forward. This can only to some extent be explained by mechanical laws. Wærsted and Westgaard (1996) found in a VDU-based laboratory task that also with *high attention demands* but *minimised physical activity* the trapezius muscle can be highly active.

From this it can be expected that the combined stress from fast physical activity and high attention can induce high trapezius activity, especially in combination with real-life factors such as long working hours, visual strain or psychological stress. But Blangsted et al (2004) found no difference in static and median EMG and in gap times, when psychosocial load was added to keying work. It is however questionable to what extend psychosocial stress can be provoked in a laboratory setting.

As certain subjects did not show co-activity at all it can be assumed that trapezius and upper arm activation are, biomechanically, not necessarily required for the completion of a task like finger tapping. This may be one reason why some VDU users are developing WRMD while others remain healthy. It is important that such individual variations are taken into consideration when planning ergonomic optimisation. It also suggests that individuals with unappropriate motor patterns may improve these by neuromotor re-education.

If it should turn out that ongoing trapezius co-activity comes along with constant activity of single MUs (Cinderella hypothesis) it should be investigated, if the *level* of co-activity (as measured by the S-EMG) is at all of importance, or if low-level co-activity can be just as corruptive if caused by just one or two constantly active motor units. It should then be investigated, what other reasons cause a motor unit to remain active, if there are differences in motor unit recruitment in individuals who develop WRMD and those who do not, and if and how motor unit substitution could actively be triggered. Short breaks can stop or reduce activity and should therefore be planned often and regularly, even in the absence of any perceived muscle fatigue or pain. Breaks can be short; according to Blangsted et al (2004), breaks of 30 seconds and of four minutes have the same effect on EMG reduction. However this experiment showed that not every individual is able to achieve complete relaxation, even when told to do so with closed eyes, no other person being present in the room, and no noise or other disturbances. They need instruction on relaxation techniques.

7 Experiment 2

Motor unit activity in the trapezius muscle during fast finger tapping, data entry and rest

The second study was undertaken to test and improve intramuscular EMG methods and to investigate motor unit activity in the trapezius muscle during three-minute finger tasks including entry of three-digit numbers on a keyboard key with audio presentation at a rate of 0.5 Hz, tapping on a keyboard key with the right index finger at a rate of 5 Hz, and resting with closed eyes. Electrodes with four fine wires were used in the right trapezius muscle (pars descendens) of six healthy subjects and intramuscular EMG was recorded with three channels. MAPQuest and MAPView were used to decompose the recordings. Surface EMG was collected from the same site. The results showed motor unit activity in the trapezius muscle in one subject during rest, in two subjects during data entry, and in five subjects during tapping. Long lasting single motor unit activity was observed in two subjects during data entry and in one subject during tapping. While these findings may support the Cinderella hypothesis, the measurement periods are too short to confirm it. It will be necessary to analyse longer periods.

7.1 Objectives

In the first experiment it could be shown that the trapezius muscle was often co-activated during a simple task like finger tapping that would not normally require its activation. Co-activity even occurred during conscious relaxation, and some subjects were apparently not able to completely relax. At this point, the motor unit (MU) firing trains should be investigated for any conspicuous patterns during co-activation.

Four studies investigating trapezius muscle activity by means of intramuscular EMG (I-EMG) have been published in the preceding years, whereof three found constant MU activity and one MU substitution: i) In an experiment with long-term recordings of 10 minutes Wærsted found continuous firing of single MUs of up to 10 minutes during attention-related low-level trapezius muscle activity (Wærsted et al 1996). ii) Kadefors identified low threshold MUs in the trapezius muscle over a wide range of arm positions in short-term measurement (Kadefors et al 1999). iii) Forsman found MUs in the trapezius muscle that were active over a wide range of shoulder abduction movement as well as during work with a computer mouse (Forsman et al 1998). iv) A study covering long-term I-EMG analysis has been published by Westgaard and De Luca in 1999. They described MU substitution during five out of eight experiments of 10 min duration.

The authors of these studies have all used wire-electrodes, since electrode dislocation could occur with needle electrodes in the presence of upper limb movements. The time consuming analysis of I-EMG and the virtually impossible analysis of long-term signals with more than one or two MUs firing was an unsolved problem at the time. With a new software (MAPQuest; Gut, Moschytz 2000), capable of decomposing overlapping action potentials fast and with little user intervention in 1-channel recordings of 10 sec[1] duration, and with some script-supported handwork the data collection could now be extended to 3 minutes and 3 channels. The necessary handwork was to merge 48 10-sec-decompositions to a single track by combining the corresponding MU shapes. The experience hereof should as well serve further decomposition programme development. The four-wire electrodes were developed at the own laboratory and were to be tested under real conditions.

The MU activity was investigated with single-finger tasks including tapping (metronome-paced), data entry (by audio presentation), and rest.

7.2 Procedures

7.2.1 Subjects

The subjects were set together of three female (28-43 year old) and three male (24-37 year old) healthy adults who gave informed consent to participate. The experiments were carried out in Switzerland according to local laws. The following criteria of 'healthy' were checked upon invitation of the subjects: i) no subjective pain symptoms within the last week in neck, shoulders, arms, wrists and fingers on either side; ii) no more than seven days with pain during the past 12 months in neck, shoulders, arms, wrists and fingers on either side.

7.2.2 Preparation

Before starting the experiments, age, sex, occupation, height, weight, dominant hand, health condition, subjective pain symptoms at present and during the past 12 months in neck, shoulders, arms, wrists and fingers, and the history of illnesses were assessed by questionnaire.

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[1] Other available, qualified decomposition programmes (Stashuk and Paoli 1998; Kadefors et al 1999) had similar limitations with recordings duration.

The subjects were sitting on an ergonomic office chair (Stoll-Giroflex 33, Koblenz, Switzerland) with a back support of medium height. The heights of table and chair were adjusted so that the knees were at right angles and the thighs parallel to the floor. The working and non-working hands and arms were kept in a symmetrical and relaxed position, the upper arms hanging down, the forearms arranged in parallel to the table and to each other, the forearms resting on the table, and the back upright. The subjects were instructed to keep neck, shoulders, arms and hands relaxed. A video camera was set up in order to monitor posture and movement of the upper limbs.

7.2.3 Tasks

The subjects carried out three different tasks in randomised and balanced order, including:

a) Resting: Attempting to relax with closed eyes while sitting.

b) Data entry: Fast entry of acoustically presented, random three-digit numbers on the numeric pad of an standard keyboard. The numbers were presented from a wave file recording at a rate of one three-digit number in two seconds.

c) Tapping: Finger tapping with the index finger at a metronome-paced rate of 5 Hz on the key '5' on the numeric pad of the keyboard.

Each task had a duration of three minutes. After task b) and c) the subject recovered during a break of five minutes. The subjects were instructed to use only the right index finger, to place the right forearm and wrist on the table, and to work in their natural manner as good as they could.

7.2.4 Surface and intramuscular EMG

I-EMG from the m. trapezius pars descendens (right side) was measured with a four-wire-electrode and analysed with MAPQuest and MAPView as described in 2.3. The sampling rate was 10 kHz. Surface EMG (S-EMG) was measured from the trapezius p. descendens, finger extensor and finger flexor (right body side), but only the trapezius recordings were analysed. The surface electrodes for the trapezius muscle were placed to the left and right of the insertion point of the wire electrode. The RMS was not only computed from the surface, but also from the I-EMG (without standardisation in the latter). MVC/MVE was assessed at the beginning and at the end of the experiments. P10 and P90 values were computed as measures for static and dynamic muscle activity.

7.2.5 Subjective evaluation of effort and pain

After each task subjects indicated the effort required during the task using the Borg scale (Borg 1990). Neck, shoulder, arm, hand and finger pain was assessed using a visual analogue scale with seven ranks.

7.2.6 Statistics

Friedman rank test for dependent measurements was used to compare differences between the three tasks. The following variables were tested: effort (Borg scale), pain levels, 10th and 90th percentile (P10 and P90) of the S-EMG, number of identified MUs, and the length of the longest pause of the most active MU. Spearman correlation was used to test correlations between P10 and P90 as well as the number of identified MUs and the length of the longest pauses of the most active MU.

7.2.7 Terminology

Wire electrodes are suitable for the recording of motor unit action potentials (MUAP) during movement of upper limbs such as in the tasks of the present study. Because of the unspecified exact geometry and location of the wires within the muscle the term ‘MUAP’ is however avoided by some authors in the context of wire electrodes and replaced by ‘wire-MUAP’ (w-MUAP). Nevertheless, as there should not be any risk of confusion in the present text, the term ‘MUAP’ is maintained.

7.3 Results

7.3.1 Overview of motor unit activity

MUAPs were clearly recognised in one subject during resting, in three subjects during inputting, and in five subjects during tapping (Table 9). During inputting however one subject (subj. 3) was found to have conducted the task with an elevated right hand, so that that data was omitted in further analyses.

Choosing for each subject the most sensitive of the three channels, clear MUAPs could be recognised in 12 out of 108 segments while resting, in 35 out of 90 segments during inputting, and in 70 out of 108 segments during tapping. The number of identified MUs was significantly different among the three tasks ($p < 0.05$).

Table 9 Number of segments where MUAPs could be identified:

- - No MUAPs recognised by visual inspection
- ± Some MUAPs recognised by visual inspection, but not by MAPQuest
- + MUAPs clearly recognised by visual inspection and MAPQuest
- [ ] Data excluded from analysis (task has been conducted with an elevated right hand)

Subject	Channel	Resting			Inputting			Tapping		
		-	±	+	-	±	+	-	±	+
1	1	18	0	0	18	0	0	8	2	8
	2	18	0	0	18	0	0	4	1	13
	3	18	0	0	18	0	0	8	2	8
2	1	16	2	0	0	0	18	1	0	17
	2	18	0	0	0	0	18	1	0	17
	3	16	2	0	0	0	18	1	0	17
3	1	4	2	12	[9]	[9]	[0]	2	0	16
	2	0	18	0	[0]	[0]	[18]	1	0	17
	3	4	2	12	[9]	[9]	[0]	0	0	18
4	1	18	0	0	16	2	0	0	18	0
	2	18	0	0	16	2	0	10	3	5
	3	18	0	0	8	10	0	10	8	0
5	1	18	0	0	0	1	17	17	1	0
	2	18	0	0	17	1	0	9	9	0
	3	18	0	0	17	1	0	9	9	0
6	1	16	2	0	10	8	0	0	0	18
	2	16	2	0	11	7	0	0	0	18
	3	16	2	0	10	8	0	0	0	18

7.3.2 Activity patterns during rest

In the resting condition the P10 (P90) levels of the S-EMG were very low. They ranged from 0.1% MVE (0.2%) until 0.4% (0.7%). In subj. 3 four MUs could be identified. They were all continuously active during the first 100 s (Figure 43). The mean firing rate (MFR) of the three most active MUs was around 8.3 Hz. However the change of activity at t = 100 s was not reflected in the S-EMG.

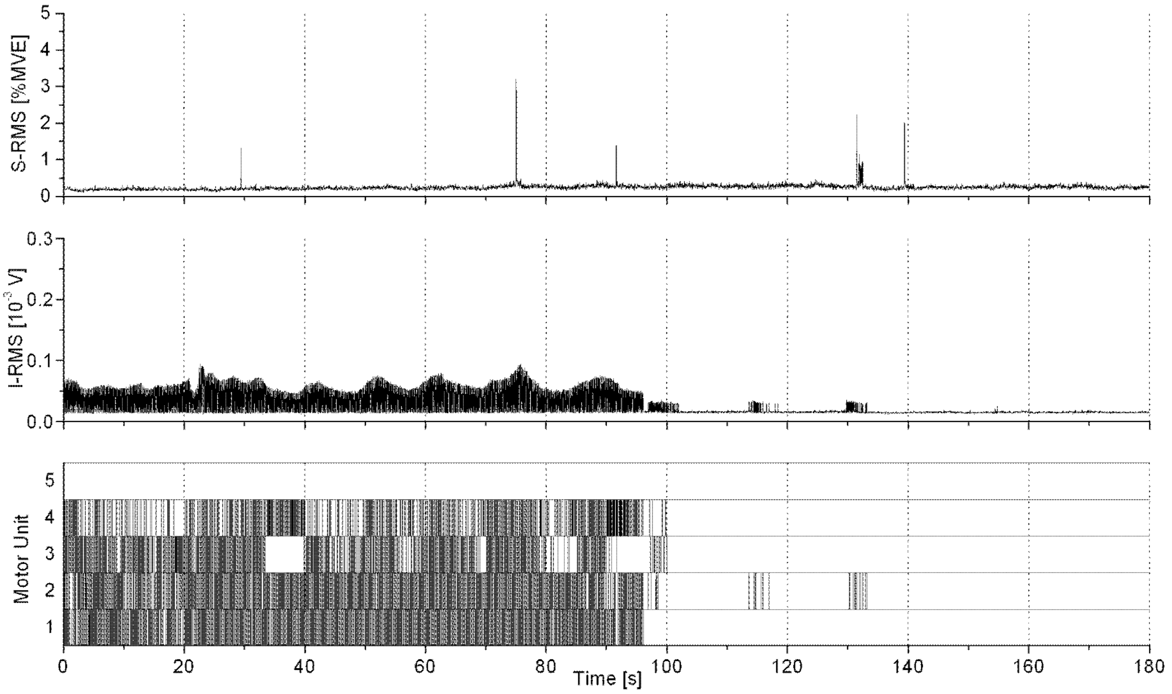

Figure 43 MU firing pattern during rest (subject 3)

7.3.3 Activity patterns during data inputting

During inputting the P10 (P90) levels of the S-EMG ranged from 0.2% MVE (0.4%) until 2.9% (7.9%). No difference in S-EMG could be observed between the three subjects with identified and the three subjects without identified MUs.

In subj. 2 (Figure 44) two MUs could be identified. With exception of the first 10 s with only few firings the most active MU (MFR 6.9 Hz) was active continuously throughout the recording period. The second MU appeared only during the first 15s with a total of no more than 10 firings. In subj. 5 three MUs could clearly be identified whereas the existence of a fourth one was doubtful (irregular firing intervals). Due to signal instability the first segment of this recording was not analysed. Two MUs stopped firing after 110 s whereas one MU continued until the end of the recording. MFR were around 6.0 Hz for the two most active MUs and 7.4 Hz for the third one.

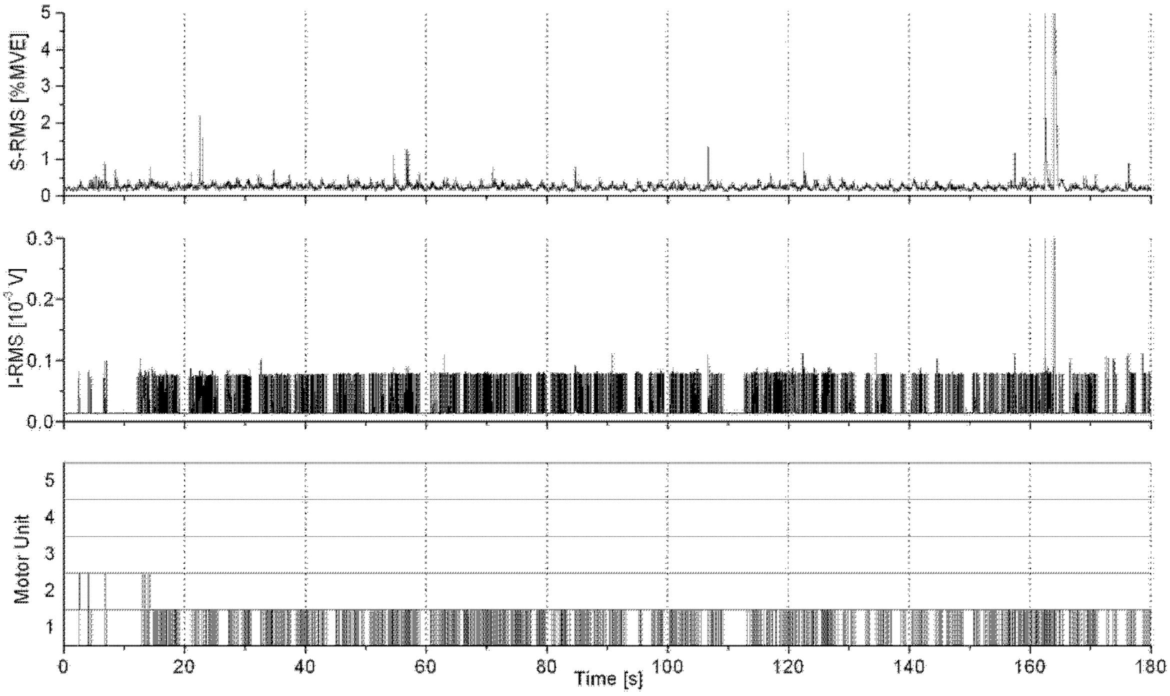

Figure 44 MU firing pattern during data inputting (subject 2)

7.3.4 Activity patterns during tapping

During tapping the P10 (P90) levels of the S-EMG ranged from 0.2% MVE (0.6%) until 1.2% (4.9%). The correlation between the P90 levels and the number of detected MUs was almost significant (Spearman R=0.75, p=0.08).

In subj. 1 (Figure 45) a consecutive onset of MUs could be observed. The first one started at about 50 s and showed regular firing from t ≈ 70 s until the recording end (MFR 12.0 Hz). Another MU set in at the same time and started regular firing at t ≈ 90 s until the end (MFR 9.6 Hz). MU no. 3 set in at t ≈ 100 s and fired, apart from minor gaps, continuously until the end (MFR 8.3 Hz). MU no. 4 finally started at t ≈ 110 s, stopped 20 s later, and set in again at t ≈ 155s (MFR 9.9 Hz). A detailed view between second 106 and 111 is shown in the bottom of the figure. At the situation '1' an increase in the S-EMG can be recognised while the I-EMG stayed low and no MUs were identified. At situation '2' on the contrary, an increase in S-EMG went along with an increase in the I-EMG as well as the number of identified MUs.

In subj. 2 continuous activity of two MUs could be observed from t ≈ 10 s until t ≈ 130 s. One of them re-appeared at t ≈ 150 s and fired until almost the recording end (MFR 7.0 and 6.6 Hz). The findings in subj. 3 might be inaccurate due to low signals. Three MUs were identified (MFR 8.5, 11.7, and 8.4 Hz). All of them started firing at t = 0 s. MUs no. 1 and 3 stopped after t ≈ 70 s while no. 2 continued until t ≈ 170 s, with a 10 s gap at t ≈ 50 s. Only one MU could be identified in subj. 4. Its onset was at t = 0 s and its duration approximately 20 s (MFR 6.2 Hz). Activity could be observed in at least six MUs in subj. 6. Two MUs were constantly active (MFR 5.9 and 5.2 Hz) while the others showed irregular patterns with substantial differences between the channels.

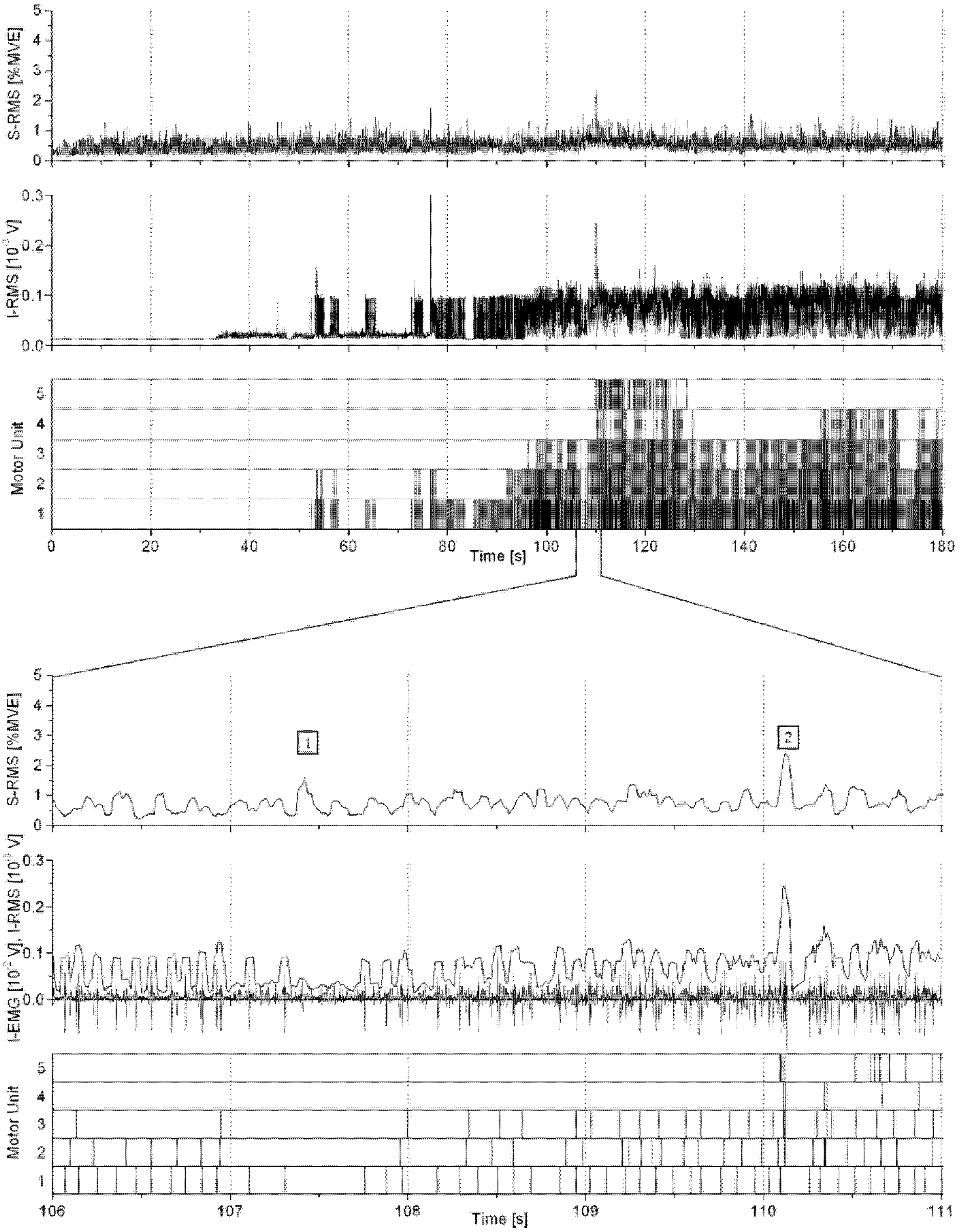

Figure 45 MU firing pattern during tapping (subject 1) (bottom: detail)

7.3.5 Number of firings and longest pauses of high activity motor units

Figure 46 shows the number of firings and the duration of the longest pause of the two most active MUs of each subject and condition. The longest pause of the most active MU during resting was 43s (subj. 3). During inputting the longest pause ranged from 2.6s (subj. 2) to 3.5s (subj. 5) and during tapping from 1.3s (subj. 6) to 130 s (subj. 4). Three MUs (two during inputting and one during tapping) could be detected whose longest inter-spike interval was 2% or less of the total task duration. This can be seen as continuous firing. No relationship between S-EMG and longest firing pause could be found.

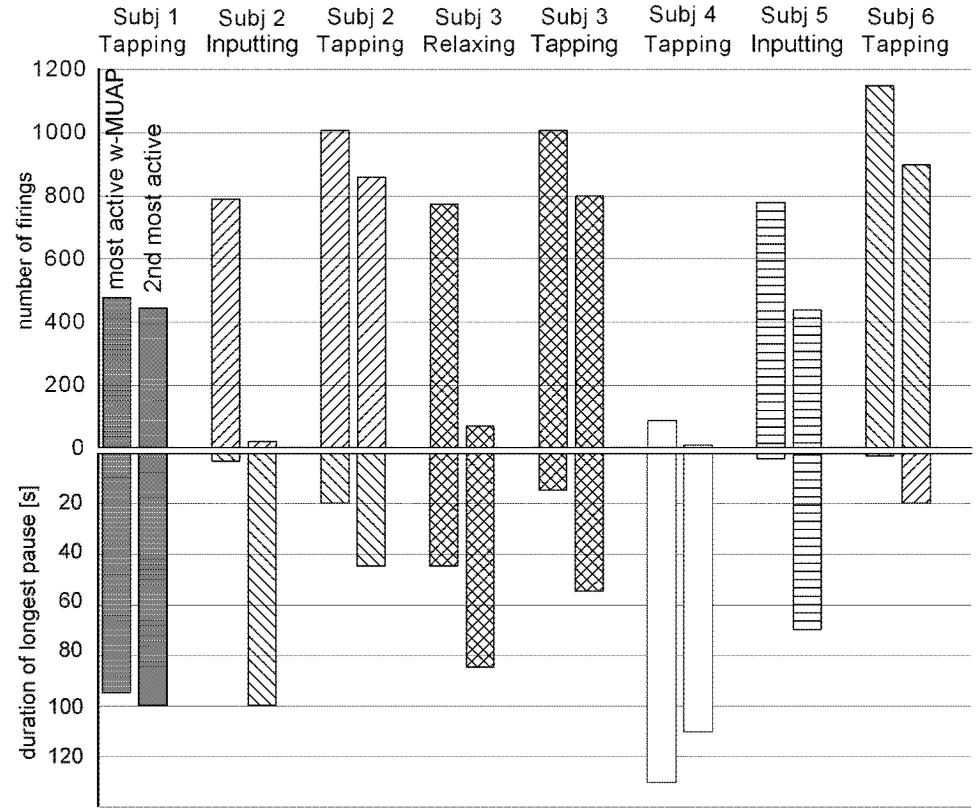

Figure 46 Number of firings and duration of longest inter-spike-interval (pause) of the two most active MUs

7.3.6 Effort and pain

The perceived effort (Borg scale) was, on average, very low during resting (0-1) and inputting (1-2). During fast tapping it was also low in the neck and shoulder (0-4) but moderately increased ($p < 0.01$) in the arm and hand (2-9). Pain was low (0-3) in all regions (including the neck) and conditions, with the exception of a moderate increase ($p = 0.04$) in the arm and hand during tapping (0-5).

7.4 Discussion

7.4.1 Decomposition programme

The combined use of MAPQuest and MAPView was sufficiently suited to analyse the three-channel, three-minute EMG. Although no exact localisation nor correction of the four wires was possible once they had been inserted, at least two channels with valid signals could be registered at all times. Comparing the results from the two or three channels the accuracy of the analysis could be verified. Limitations were encountered in registrations with a high number of MUAPs, such as the tapping of subj. 6. The manual analysis of this record took a considerably longer time and despite high MUAP amplitudes the results from the three channels were inconsistent. On the other hand very reliable results were obtained in signals with a low number of MUAPs, even if their amplitudes were small.

7.4.2 Electrode displacement

The question may arise if the observed on/off-behaviour of some MUs was due to wire displacement inside the muscle instead of an on- and offset of MU firing. Three reasons contradict this assumption: i) No movement of arms, shoulders or neck could be identified in the video recordings. Even with the presence of shoulder or arm movements it is unlikely that this would have caused electrode displacement (Kadefors et al 1999). ii) Wire displacement would most likely have had an effect on all channels simultaneously and not only on one. Simultaneous effects could not be observed. iii) The MUAPs found in subj. 2 (which was one of the two subjects where MUAPs were observed in more than one task) had high amplitudes and clear turning points, and it was easy to identify the same MUs in both tasks. This suggests that the wires stayed in place even during the break between the two tasks.

7.4.3 Discomfort

Although the presence of wires could be noticed by the subjects, the perceived pain was minimal in the neck. The pain levels did not differ from those in arms and hands. The fact that pain levels indicated after three minutes of tapping were significantly higher than in the beginning provides evidence that the visual pain scale was appropriate to register slightly elevated pain levels.

7.4.4 Motor unit activity in the trapezius muscle

A correlation could be observed between S-EMG (especially P90) and the number of active MUs. However it was not possible to identify a statistically relevant measure from S-EMG that would predict an absence of MU activity. This poor relationship should not be considered an artefact because the wires were positioned exactly under the surface electrodes. A possible explanation is that low-threshold MUs would be very small, consisting of only a small number of fibres. Depending on their exact localisation they could easily be missed by the wires. I-EMG detection would therefore include a random selection of MUs. To overcome such restrictions the number of subjects and recordings should be high, but such analysis can only be achieved with future, fully automated decomposition programmes allowing long-term analysis. Because of these limitations, the described results are of qualitative nature.

Prolonged firing of the same MU could be observed even while resting. One subject with constant activity and no substitution of four MUs during the first 100 seconds of the resting task seemed to be relaxed, but obviously the relaxation was insufficient to stop MU activity in the trapezius muscle. Maybe there was some effect coming from her previous task which was tapping; however in the first experiment, prolonged static trapezius muscle activity while resting had already been found. The incomplete relaxation of the neck was thus due to continuous firing of single MUs in this specific subject.

Trapezius muscle MU activity was also observed during inputting in two subjects and during tapping in five subjects. A higher number of MUAPs could be observed during tapping compared to inputting ($p = 0.2$). The lack of statistical significance may be due to the limited number of subjects. While the continuous and extended MU activity during the full three minute registration found in three subjects may support the Cinderella hypothesis, the recording time was too short to confirm it. The substitutions that Westgaard and De Luca (1999) have found have all set in after three minutes or later. On the other hand clear MU substitution was not found either, but a rather random pattern of on- and offset of firings.

In this experiment subjects worked at an ergonomically designed workstation, resulting in a relaxed and comfortable body posture. The subjective effort in the neck muscles was minimal. Nevertheless continuous activity of MUs could be observed in some of the registrations. The three-minute tasks contained elements of office work and required little mental concentration. The experiments gave indication that during day-long office work, especially when in combination with factors like high mental demand or social stress, MUs may be active during extended periods. In order to clarify this assumption, considerably longer registrations are required.

8 Experiment 3

Muscle strain in the trapezius and finger muscles in the comparison of a computer mouse and a pen

The findings on trapezius muscle co-activity with simple tasks involving the index finger were to be expanded to tasks with real-life settings (clicking/drag-and-drop) and compared between two pointing devices requiring different finger mechanics, i.e., mouse and pen. The effects of co-activity on the firing patterns of motor units were to be investigated. Perceived effort and pain were collected by questionnaire, performance determined as the number of clicks or drags per time. With event-triggered techniques applied on the surface and intramuscular EMG (cumulative sums), co-activity very closely linked to the finger movement could be demonstrated also on the level of single motor units. The pen was related to less co-activity, less effort and better performance. Ongoing motor unit activity (Cinderella) in the trapezius was seen with the mouse and with the pen. The results also show that, with clicking, single trapezius motor units may be co-activated which would be masked in the surface EMG. Surface EMG can't therefore suffice to predict if a computer user is going to develop WRMD in the trapezius due to ongoing co-activity of single motor units.

8.1 Objectives

In the preceding experiments it was found that the trapezius muscle is active in susceptible subjects with simple finger tasks such as tapping or single-finger data inputting. In other subjects the trapezius did not respond to finger activity. It was also found that single motor units (MU) were active continuously, i.e. at least during the recording time of three minutes (experiment 2), even if the overall muscle activity registered by the surface EMG (S-EMG) was close to zero.

In the last experiment the finger tapping is expanded to operating a pointing device. Two devices were compared that use different finger mechanics: a traditional mouse, and a pen with tablet. Operating a pointing device involves additional motor patterns besides the basic finger movement known from tapping (repetitive ballistic movements; see 4.4). Intensive single-clicking, double-clicking and drag-and-dropping was executed in tasks of nine minutes duration.

A pen is operated on a tablet with a relatively small surface so positioning can be achieved with the fine-motor finger muscles instead the gross-motor arm and shoulder muscles. The resting position is close to the neutral hand position. To drag, the pen is moved over the surface as if to draw a line with a pencil. Clicking (touching the tablet surface shortly with the pen tip) is realised with little force and there is no need for permanent elevation of the fingers over a mouse button. The tablet is connected to the computer, the pen itself is wire- and batteryless and coupled to the tablet electrostatically. While pens are often used in graphics industries (with larger tablets however), they are not yet very common in offices

The comparison took place in experimental sessions of about three hours. Because of the fundamental differences in operating a mouse and a pen, some of the strenuous factors associated with the mouse (see 2.3) were expected to be reduced. Interest was also paid to doublets that had been found to be increased during the acceleration phase of double-clicking in the extensor communis digitorum (Sjøgaard et al 2001) and in the ipsi- and contralateral trapezius muscle in one out of twelve subjects (Olsen et al 2001). The outcomes may be biased because all subjects were experienced mouse users, but had never used a pen, except for the introduction to the experiment a day before. Still we expected:

- reduced pain and surface and intramuscular EMG levels in all investigated muscles with resting, compared to working
- reduced effort, pain and surface and intramuscular EMG levels in all investigated muscles and better performance with the pen
- reduced effort, pain and surface and intramuscular EMG levels in all investigated muscles and better performance with single-clicking, compared to double-clicking

8.2 Procedures

8.2.1 Subjects

20 healthy, right-handed subjects using the computer and the mouse for at least 10 hours per week gave informed consent to participate in this study. They affirmed that they did not suffer from actual musculoskeletal disorders in the neck, shoulders, arms or hands. All subjects used a mouse in their computer work and no one used a pen. Approval for this study was obtained from the ethical committee of the University Clinic of Zurich.

Because there were issues with the I-EMG (see below), the experiments had to be stopped with 6 subjects after the wire electrode insertion. Another experiment was stopped because the subject felt discomfort at the insertion site after a part of the experiment. The remaining group of 13 subjects consisted of four females and nine males with a mean age of 32 ± 5 years.

8.2.2 Electromyography

Differential S-EMG was measured with bipolar surface electrodes from the trapezius p. descendens (TRD), extensor digitorum communis (EXT), and flexor digitorum superficialis (FLE) muscles of the right body side. I-EMG was measured from the trapezius p. descendens with a four-wire-electrode, inserted between the two surface electrodes. Signal decomposition was realised with EMG-LODEC. For details on EMG methods see chapters 5.1 and 5.2.

Because of insufficient I-EMG quality, either due to high environmental electromagnetic noise or bad electrode placement (e.g. in connective tissue), the experiments with six subjects had to be stopped. In contrast to needle electrodes, wire electrodes, once inserted, can't be adjusted and corrected to find an optimal location with motor unit action potentials visible in all channels. In such a case, the subjects were given the option to leave, but most of them agreed to stay for a second attempt with a new electrode.

8.2.3 Mouse and Pen

The tasks were carried out with a standard mouse and a pen in randomised and balanced order. The mouse was a two-button mouse of rectangular shape (Compaq M-SF 14-2; 100 x 56mm, Figure 47 left). The settings under Windows 2000 were: double-click speed *medium*[1], pointer speed *medium*, and pointer acceleration *low*.

The pen (Wacom ET-0405-U, Figure 47 right) had a length of about 145 mm and a diameter of 10 - 13 mm and was used on a tablet with a total area of 209 x 214 mm and an active area of 127 x 93 mm (the area within the white rectangle)[2]. Settings: double-click speed medium, double-click distance 10 pixels, tip pressure feel medium, click force 8%, reported pressure 8%, tip force 31%.

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[1] Some setup routines did not allow numeric inputs but only sliders for 'low – medium – high' or percentage values.

[2] Other technical data: coordinate resolution 40 lpmm, accuracy ± 0.5 mm, sampling rate 100 Hz, pressure levels 512, pen tip travel ≤ 0.1 mm, pen weight 11g.

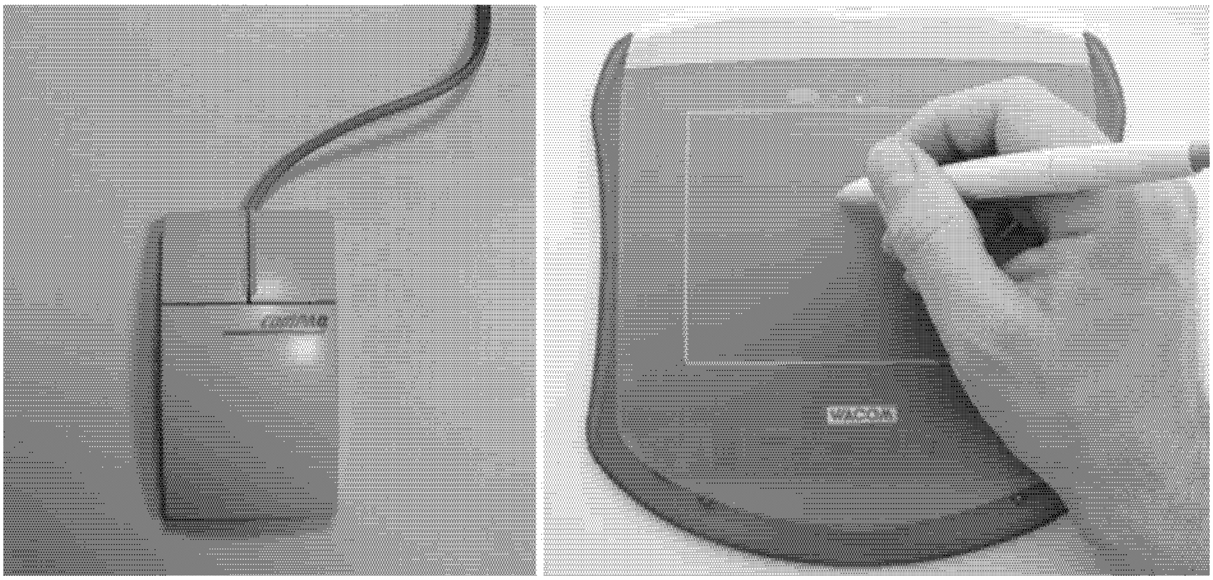

Figure 47 Mouse and pen with tablet

The pen allowed two mapping modes, called pen mode and mouse mode. Pen mode, which was chosen, uses an absolute positioning where the active tablet area is a direct mapping of the computer screen (the left top corner of the pad corresponds to the left top corner of the screen and the right bottom corner of the pad to the right bottom corner of the screen). This allows to position the screen pointer very fast without having to 'pick up' and roll it as with a mouse or with the mouse mode of the device.

The subjects were not familiar with the pen and took part in a half-hour instruction and practice one or two days before the experiment.

Pen operation: For pointing, the pen tip can either be placed and dragged with light pressure on the tablet. Alternatively – and more safely – it can be dragged within a proximity of about 5mm; this avoids accidental clicking or drag-and-dropping. For larger dislocations, the pen can be raised from the tablet completely; the pointer will jump to the new location as soon as the pen tip regains the 5 mm proximity. Clicking is achieved by tapping the tablet once with the pen tip; for a double-click, the tablet is tapped twice within a certain time delay (set to medium) and area (set to 10 px, i.e. 1.24 mm in the horizontal and 1.21 mm in the vertical direction at the given screen resolution). The lateral button, that could alternatively be used for double-clicking, was avoided in order to achieve results that are comparable with those of the mouse. To drag-and-drop an object, the pen must stay in contact with the tablet and exceed a certain pressure force while sliding (as if to draw a line with a pencil).

8.2.4 Workplace Setup

The subjects were sitting on an ergonomic office chair with a back support of medium height (Girsberger Pronto). The desk was slightly reclined by 5° for an optimal ergonomic setting. The heights of table and chair were adjusted so that the forearms could be placed horizontally and relaxed on the desk. The knees were at right angles and the thighs parallel to the floor. The back rest was adjusted to a vertical position in the lower and a slight incline in the upper part. The subjects were instructed to keep their upper body in a comfortable, more or less upright position.

A TFT flat screen (TFT Philips151AX 15.1') with 1024x768 pixels resolution was placed at 75 cm from the desk front edge. The mouse mat or tablet was placed to the right of the keyboard, comfortably for the subject. The mouse and the tablet had to be swapped between the tasks, but it was made sure that their placement was always more or less the same. The tasks were presented in a Windows Internet Explorer window in full screen mode with a black background and no navigation, scroll or status bars or window borders (except for a right scroll bar in the text search subtask of the drag-and-drop task, see below). The tasks were programmed in HTML and JavaScript.

8.2.5 Task sequence

The tasks involved intensive, semi-natural work with the pointing devices. Block A consisted of the four tasks 'mouse single-clicking' (AMS), 'pen single-clicking' (APS), 'mouse double-clicking' (AMD) and 'pen double-clicking' (APD), comparing single-clicking with double-clicking and mouse with pen. In block B, drag-and-drop was compared in the 'mouse drag-and-drop' (BM) and 'pen drag-and-drop' (BP) tasks. The tasks were randomised within the A and B blocks and combined with rests (R1…R4) with EMG assessment as shown in Table 10. Maximum voluntary contraction (MVC) was performed three times (see below). The T, L and R4 tasks belong to a different question not analysed in this study, comparing the EMG in resting after intensive computer work, followed by a weight training session or a break used for relaxed reading of a magazine or book.

Table 10 Task sequence

Sequence	Task	Description	Duration
1	MVC1	Maximum voluntary contraction with trapezius, finger extensor and finger flexor muscles	
2	MVC2	Maximum voluntary contraction with finger extensor and finger flexor muscles	
3	R1	Resting	5 min
4-7	Block A	4 tasks in randomised and balanced order: - AMS (mouse single-clicking) - APS (pen single-clicking) - AMD (mouse double-clicking) - APD (pen double-clicking)	 9 min 9 min 9 min 9 min
8	R2	Resting	5 min
9-10	Block B	2 tasks in randomised and balanced order: - BM (mouse drag-and-drop) - BP (pen drag-and-drop)	 9 min 9 min
11	R3	Resting	5 min
12	T/L	Weight-training (T) or relaxed reading (L)	~20 min
13	R4	Resting	5 min
14	MVC3	Maximum voluntary contraction with trapezius, finger extensor and finger flexor muscles	

Block A: Single- and double-clicking

Block A contained the four tasks AMS, AMD, APS and APD in randomised and balanced order. While the pointing device and actuation mode (single or double clicking) was changed, the presented 'job' was the same for the four tasks and consisted of clicking on different objects on the screen. Each task had a duration of 9 minutes and was set together of subtasks with a duration of 1 minute each. While the main subtask A1 was repeated every second minute, the subtasks A2…A5 appeared only once, thus the sequence was A1 - A2 - A1 - A3 - A1 - A4 - A1 - A5 - A1.

Subtask A1, the main subtask, was of medium motor and low visual demand. These demands varied in the other subtasks. After each minute the programme jumped to the next subtask, regardless of how much of the previous one was completed. The subtasks were not designed to be completed after one minute. Generally, the objects had to be clicked on, which caused them to jump to a new position. The java script differed only in that it reacted after a single click in AMS and APS and after a double click in AMD and APD. A detailed description of the subtasks with screenshots is provided in the appendix.

Block B: Drag-and-Drop

Block B contained the two tasks BM and BP in randomised and balanced order. While the pointing device was changed, the presented 'job' was the same and consisted of dragging and dropping of different objects on the screen. Each task had a duration of 9 minutes and was set together of subtasks with a duration of 1 minute each. While the main subtask B1 was repeated every second minute, the subtasks B2…B5 appeared only once, thus the sequence was B1 - B2 - B1 - B3 - B1 - B4 - B1 - B5 - B1.

Subtask B1, the main subtask, was of medium motor and medium visual demand. These demands varied in the other subtasks. After each minute the programme jumped to the next subtask, regardless of how much of the previous one was completed. The subtasks were not designed to be completed after one minute. Generally the objects had to be dragged to a specific position and dropped. They could be moved freely and smoothly over the screen and were fully visible during dragging. A detailed description of the subtasks with screenshots is provided in the appendix.

8.2.6 Resting and MVC/MVE

Four resting sessions (R1…R4; R4 not included in the analysis) with EMG measurement were included as listed in Table 10. The subjects were instructed to relax as completely as possible, especially in their neck and arms, while leaning comfortably against the backrest and keeping the eyes closed.

Maximum voluntary contraction measurements (MVC/MVE) were performed three times: After attaching the S-EMG electrodes (MVC1), after inserting the intramuscular wire electrode in the trapezius muscle (MVC2), and at the end of the experimental session (MVC3). In order to not displace the intramuscular electrode in the trapezius muscle, MVC2 was only performed with the finger extensor and flexor. MVC1 and MVC3 included the trapezius muscle as well.

8.2.7 Mouse and pen activity

Hardware solutions were developed to measure mouse and pen activity (clicking). In the mouse, the voltage over the button switch was measured. In the tablet, the light from the built-in LED (light-emitting diode) was measured by a photo resistor placed over the LED. The photo resistor measured the change in light intensity when the LED changed from yellow to green during pen pressing. Both signals were converted to 0/+5V levels, sampled at 20 kHz, and recorded with LabView along with all other signals.

8.2.8 Questionnaires and video monitoring

Subjective perception of effort and pain in the hand, forearm, upper arm, shoulder and neck of the right body side was assessed before the experiments and after each task. A 10 rank Borg scale was used for effort (0 = no effort at all, 9 = extremely high effort) and a 7 rank scale for pain (0 = no pain at all, 6 = extreme pain). The perception of the left body side was only assessed between the task blocks. A video camera was set up to monitor posture and motion of the upper limbs.

8.2.9 Analysis

The statistical evaluation was made on parameters of performance, S-EMG, I-EMG and questionnaire answers, comparing the conditions AMS, APS, AMD, APD, BM, BP, Rest and Work (for definitions see Table 10). The rest conditions R1, R2 and R3 were combined to the condition 'Rest' (mean value). For the 'Work' condition the mean value was calculated from AMS, APS, AMD, APD, BM and BP.

Performance parameters

The performance was determined from the registered clicking activity during the main subtasks, thus during the minutes 1, 3, 5, 7 and 9. The mean click duration was named CLID, the mean interclick interval (the sum of click and release durations) ICLI. ICLI is the inverse of the number of clicks per time, CLID stands for the time that the pointing device is actively pressed. For the exact definition see Figure 48.[1]

- ICLI: mean interclick interval
- CLID: mean click duration

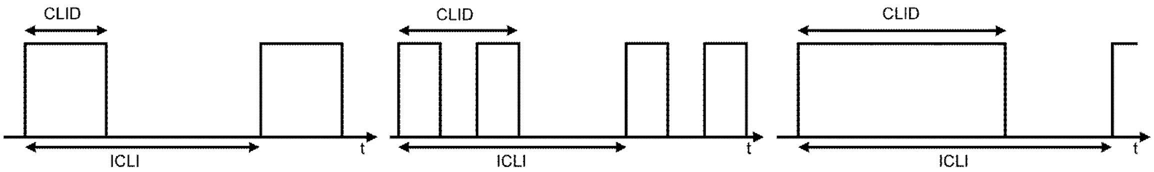

Figure 48 Definition of ICLI (mean interclick interval) and CLID (mean click duration) in single-clicking (left), double-clickings (middle) and drag-and-drop (right)

S-EMG parameters

The median S-EMG values were calculated only from the main subtasks and further divided into clicking and release phases. In the resting tasks, the parameters were determined from the whole signal.

- $SEMG_{tra,cli}$: S-EMG of trapezius p. descendens during clicking

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[1] Terminology: The terms 'click' and 'clicking' and the index 'cli' mean any sort of pointing device activation (the duration of which is CLID), be it a single-click, a double-click or a drag-and-drop, be it with the mouse or with the pen. A double-click consists of two 'sub-clicks'. The 'release' duration is the time between two clicks (= ICLI – CLID).

- SEMG$_{tra,rel}$: S-EMG trapezius p. descendens during release of the mouse/pen
- SEMG$_{ext,cli}$: S-EMG finger extensor during clicking
- SEMG$_{ext,rel}$: S-EMG finger extensor during release of the mouse/pen
- SEMG$_{fle,cli}$: S-EMG finger flexor during clicking
- SEMG$_{fle,rel}$: S-EMG finger flexor during release of the mouse/pen

I-EMG parameters

The following parameters were calculated from the EMG-LODEC output files, including all subtasks:

- #MU: Number of detected motor units (MUs)
- #MU$_{1000}$: Number of detected MUs with at least 1000 action potentials during the 9 minutes
- #MUAP: Total number of action potentials of all MUs
- #SIMU$_{mean}$: Mean number of simultaneously active MUs in a trial. Simultaneity was defined as 'occurring within the same 1 second window'.
- #SIMU$_{max}$: Maximum number of simultaneously active MUs in a trial
- %ACT: Percentage of time with at least one active MU
- #COMU: Number of continuously active MUs in a trial. Continuity was defined as 'sum of all interspike-intervals shorter than 1s is greater than 90% of the total trial duration'
- #DOUB: Number of doublets. Following common guidelines, two action potentials of the same MU were considered a doublet if occurring within 20 ms.

Questionnaire parameters

The questionnaire answers were assigned to the following parameters:

- EFFO$_{r,hand}$: effort right hand
- EFFO$_{r,f\text{-}arm}$: effort right forearm
- EFFO$_{r,u\text{-}arm}$: effort right upper arm
- EFFO$_{r,shou}$: effort right shoulder
- EFFO$_{r,neck}$: effort right neck
- PAIN$_{r,hand}$: pain right hand
- PAIN$_{r,\text{-}earm}$: pain right forearm
- PAIN$_{r,u\text{-}arm}$: pain right upper arm
- PAIN$_{r,shou}$: pain right shoulder
- PAIN$_{r,neck}$: pain right neck

The perception of the left body side was not included in the analysis.

Statistical analysis

The different parameters were compared between the conditions using signed rank testing:

- Comparison 1: Resting ↔ working (mean of all resting tasks (R1, R2, R3) compared with mean of all working tasks (AMS, APS, AMD, APD, BM, BP))
- Comparison 2: AMS ↔ APS (mouse compared with pen during single-clicking)
- Comparison 3: AMD ↔ APD (mouse compared with pen during double-clicking)
- Comparison 4: BM ↔ BP (mouse compared with pen during drag-and-drop)

- Comparison 5: AMS ↔ AMD (single-clicking compared with double-clicking using the mouse)
- Comparison 6: APS ↔ APD (single-clicking compared with double-clicking using the pen)

Event triggered S-EMG

From the main subtasks of blocks A and B, trapezius S-EMG intervals of 1000 ms duration containing a click were superimposed. Only segments containing a click with a duration (CLID) within the interquartiles of the particular trial and subject were used. The alignment was made at the start of the click, adding a leading 500 ms. From the superpositions, mean/sd graphs were computed.

Event triggered I-EMG (cusum)

A peristimulus time histogram is a correlogram between a stimulus and the discharge train of impulses of a neuron and is formed from the sum of a number of trials. Typical peristimulus time histograms scatter quickly around a mean level and changes in the mean level (as a reaction to an external stimulus, e.g.) are small compared to the scatter and hard to detect by eye. A cusum (cumulative sum) chart is a simple statistical technique which makes changes in the mean level appear as changes in the slope. It is derived as follows (Ellaway 1978): A reference level (k) is subtracted from each of the series of points on the histogram (x_1, x_2,..., x_n) in turn. A new series of points (S_i) is formed by adding up these differences consecutively. The cusum chart is the sequential plot of the values of S_i:

$$\begin{aligned} S_1 &= (x_1 - k) \\ S_2 &= S_1 + (x_2 - k) = x_1 + x_2 - 2k \\ S_3 &= S_2 + (x_3 - k) = x_1 + x_2 + x_3 - 3k \end{aligned}$$

$$S_i = \sum_{i=1}^{k} (x_i - k)$$

The selection of the appropriate level (k) depends upon the task in hand; often, the mean occurring in a reference period is chosen. The value of the slope during a period of change in the mean level is equal to the difference of the mean level during this period and the reference level.

The variance of the cusum at times *t* after a control reference period of duration *u* can be expressed as

$$V_{t>>0} = n\left[\frac{c^2 t}{m} + \frac{1}{6} - \frac{c^4}{6} + \frac{(ct)^2}{um}\right] \quad \text{(t >> 0)}$$

and

$$V_{t\to 0} = \frac{nt}{m} \text{ (small t) (Poisson process)}$$

where *c* is the coefficient of variation and *m* is the mean interval of the discharge train used to construct a peristimulus time histogram of *n* trials (Davey et al 1986). In practice, one can calculate the variance values for all t's with both formulas and then use only the smaller of the two values at each time t:

$$V(t) = \min(V_{t\to 0}(t), V_{t>>0}(t))$$

Davey et al suggest to use confidence intervals equal to 3 times the variance values.

In the present cusum calculations of the mouse and pen single-clicking trials (AMS and APS), the click start was used as the trigger. For each MU, all intervals starting 350 ms before and ending 350 ms after the start of a click were superimposed, adding up all MU action potentials into 1ms bins. The first 200 ms (350...150 ms before the click) were used as the reference period. Its mean gave the cusum reference value k. Only clicks with a duration within the interquartiles of the particular trial and subject were included, and a mean firing rate of at least 10 Hz during the 700 ms interval (thus 7 firings) was required. Only MUs with at least 100 clicks meeting these conditions were included in the cusum analysis. Confidence intervals corresponding to 3 times the variance as proposed by Davey et al were computed and plotted above and below the level k, with the vertex at t = -150 ms (see Figure 60).

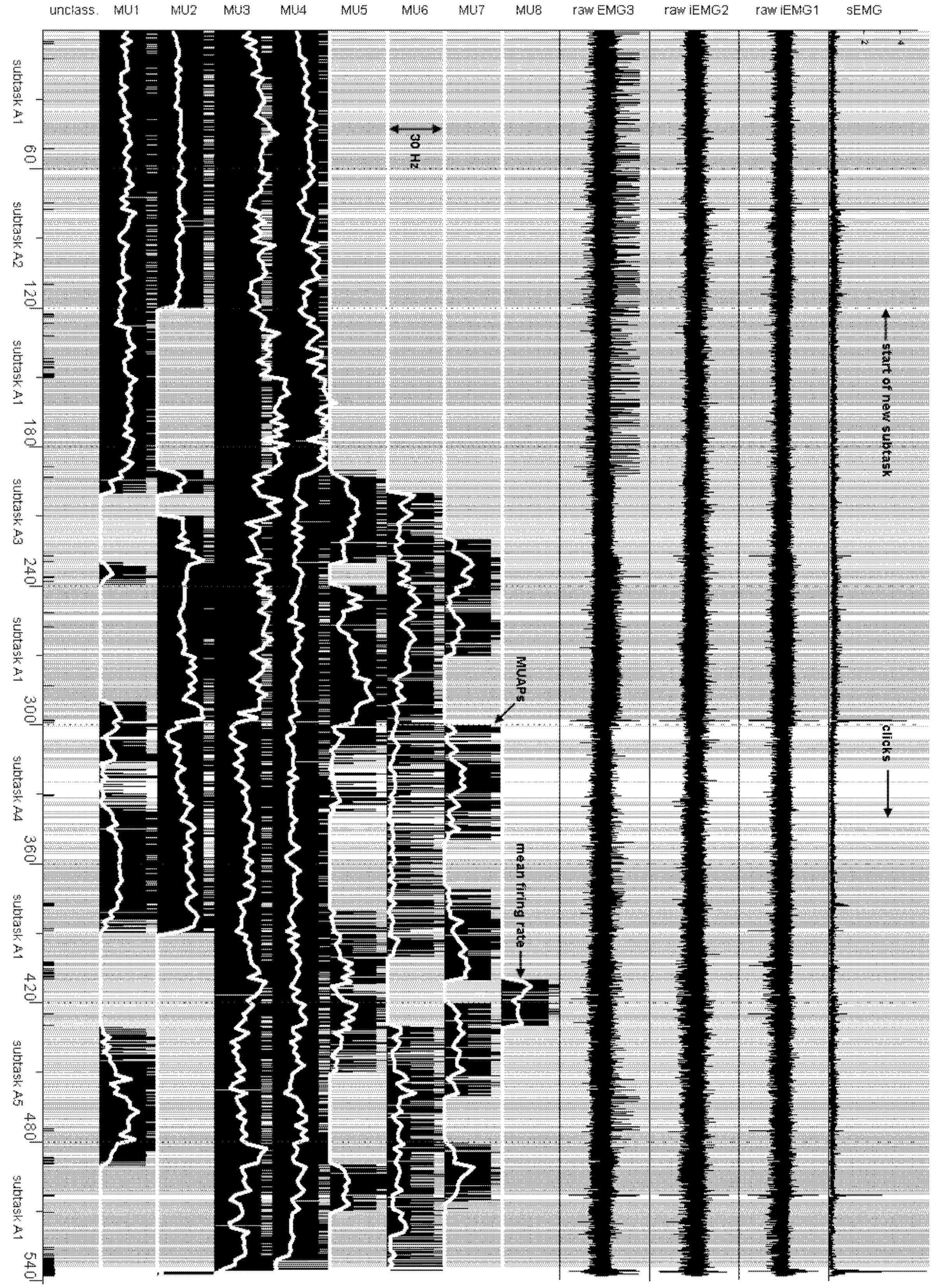


Figure 49 Example of a plot of the temporal course of S-EMG, I-EMG and clicking (subject 2, AMS). The different MUAP line heights represent the decomposition quality (reliability) as reported by EMG-LODEC (longest line = best quality)

8.3 Results

8.3.1 Data quality

Very high numbers of MUs (up to 50) were found in some measurements, mainly in subject 10 and 4. This seemed to be a result from a too conservative MU merging by EMG-LODEC, particularly after firing gaps. These two subjects were therefore excluded from the statistical analysis. Two other subjects (1 and 3) were unable to double-click with the pen; instead of twice they clicked three or four times or held the pen at such an angle that the tip slid over the tablet and the system interpreted some clicks as drag-and-drops. These two subjects were also excluded from the analysis. With only 9 remaining subjects (one female and eight male), large parameter ranges and non-normal distributions, mean/sd notations were unsuitable. An overview was therefore created by box plots with individual and median values.

The parameter values from R1, R2 and R3 did not statistically differ ($0.03 \le F \le 1.46$) so that R1, R2 and R3 could be combined to the condition ‘Rest’ or ‘R’ (mean value). The temporal course of S-EMG, I-EMG and clicking was plotted as in Figure 49 in order to gain an overview, e.g. on the frequent on- or offsettings of MUs with the start of a new subtask.

8.3.2 Performance

Working with the pen was significantly faster in terms of the mean interclick-interval ICLI (thus more clicks per time) than with the mouse in one (out of three) mouse-pen comparisons (Table 11). Pen clicks were significantly shorter than mouse clicks in two (out of three) mouse-pen comparisons (CLID). For the remaining mouse-pen comparisons, the box plots suggest a tendentially better performance with the pen (Figure 50). Single-clicking was significantly faster (ICLI and CLID) than double-clicking in all comparisons.

Table 11 Significant signed rank tests of performance parameters ICLI (mean interclick-interval) and CLID (mean clicking duration). The cells contain the conditions with the lower parameter (* $p < 0.05$; ** $p < 0.01$) (9 subjects).

		mouse ↔ pen			s-click ↔ d-click	
	Rest↔Work	**AMS↔APS** s-click	**AMD↔APD** d-click	**BM↔BP** dr&dr	**AMS↔AMD** mouse	**APS↔APD** pen
ICLI	n.a.		APD** (pen)		AMS** (s-click)	APS** (s-click)
CLID	n.a.	APS** (pen)	APD** (pen)		AMS** (s-click)	APS** (s-click)

(ICLI and CLID not available for rest)

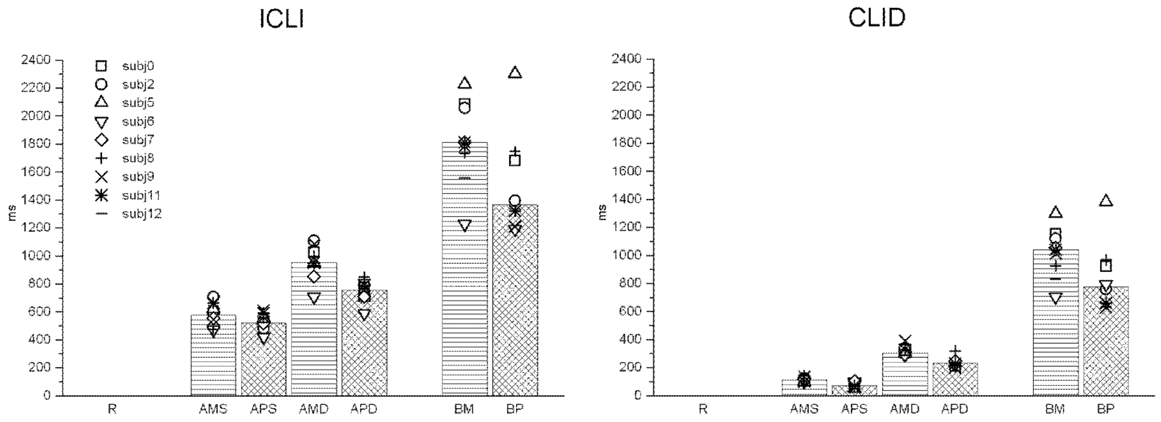


Figure 50 Mean interclick interval (ICLI) and mean click duration (ICLI) (median and individual values)

8.3.3 Effort and Pain

Table 12 Significant signed rank tests of effort (EFFO) and pain (PAIN) of the right hand, forearm and neck. The cells contain the conditions with the lower parameter (* p < 0.05; ** p < 0.01) (9 subjects).

		mouse ↔ pen			s-click ↔ d-click	
	Rest↔Work	**AMS↔APS** s-click	**AMD↔APD** d-click	**BM↔BP** dr&dr	**AMS↔AMD** mouse	**APS↔APD** pen
EFFO$_{r,hand}$	n.a.	APS* (pen)	APD* (pen)	BP* (pen)		
EFFO$_{r,f\text{-}arm}$	n.a.	APS** (pen)	APD* (pen)			
EFFO$_{r,neck}$	n.a.	APS* (pen)				
PAIN$_{r,neck}$						

(effort parameters not available for rest)

Effort: The perceived effort was rated significantly lower with the pen in the hand (in all three mouse ↔ pen comparisons), in the forearm (in two comparisons), and in the neck (in one comparison) (Table 12, Figure 51, Figure 52). The effort parameters of the upper arm and shoulder were mostly zero and could not be statistically evaluated.

Pain: The perceived neck pain was not rated significantly different in resting and working, nor between the pointing devices, though tendentially lower with the pen in single-clicking and drag-and-drop (Figure 52). The pain parameters from the hand, forearm, upper arm and shoulder were mostly zero and could not be included in the statistical analysis. Still, indications of pain > 0 were more than twice as frequent with the mouse in those body parts, compared to the pen, as listed in Table 13. In resting, pain indications were always zero in the hand, forearm, upper arm and shoulder.

Table 13 Number of indications of pain > 0 on the Borg scale in the right hand, forearm, upper arm, shoulder and neck, per task and summed up per input device (9 subjects).

	Mouse				Pen			
	AMS s-click	**AMD** d-click	**BM** dr&dr	**Sum**	**APS** s-click	**APD** d-click	**BP** dr&dr	**Sum**
$\text{PAIN}_{r,hand}$	2	2	2	6	1	1	1	3
$\text{PAIN}_{r,f\text{-}arm}$	4	2	4	10	0	1	3	4
$\text{PAIN}_{r,u\text{-}arm}$	1	0	1	2	0	0	0	0
$\text{PAIN}_{r,shou}$	1	0	1	2	0	0	1	1
$\text{PAIN}_{r,neck}$	7	5	5	17	5	5	4	14
Sum	(without neck)			20	(without neck)			8

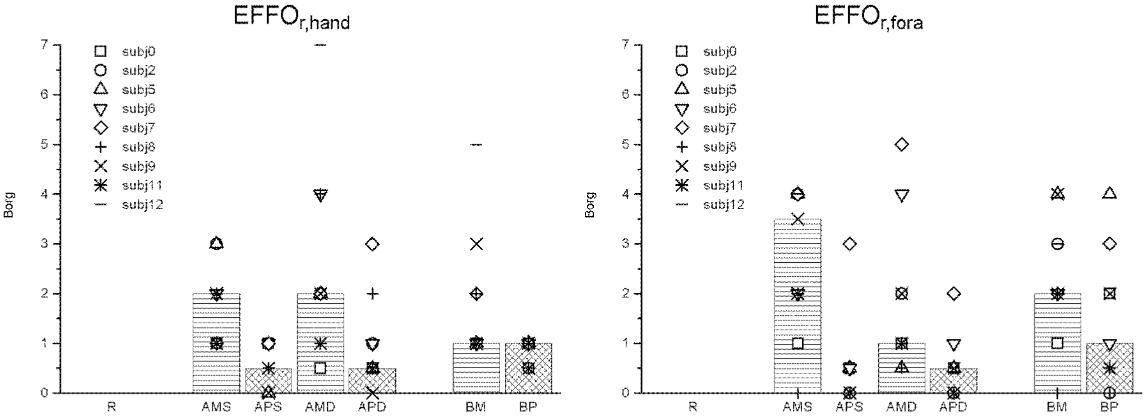


Figure 51 Perceived effort in the right hand ($\text{EFFO}_{r,hand}$) and forearm ($\text{EFFO}_{r,fora}$) (median and individual values)

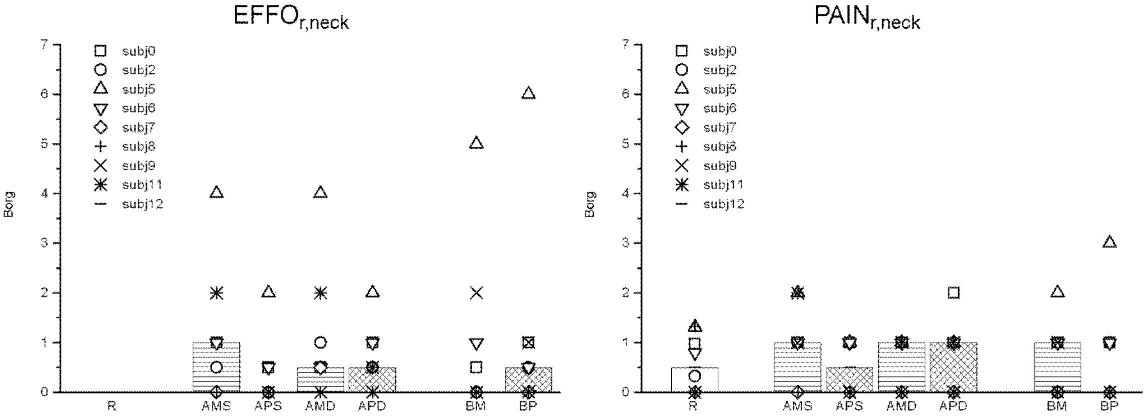


Figure 52 Perceived effort in the right side of the neck ($\text{EFFO}_{r,neck}$) and neck pain ($\text{PAIN}_{r,neck}$) (median and individual values)

8.3.4 S-EMG parameters

Finger extensor: The S-EMG was significantly lower in resting than in working (Rest ↔ Work) (Table 14, Figure 53), when drag-and-dropping with the pen instead the mouse (BM ↔ BP), when double-clicking instead single-clicking with the mouse (AMS ↔ AMD), and when double-clicking instead single-clicking with the pen (only during clicking pauses) (APS ↔ APD).

Finger flexor: The S-EMG was significantly lower in resting than in working (Rest ↔ Work), when single-clicking with the pen instead the mouse (only during clicking) (AMS ↔ APS), when drag-and-dropping with the mouse instead the pen (only during clicking) (BM ↔ BP), and when double-clicking instead single-clicking with the mouse (only during clicking pauses) (AMS ↔ AMD).

Trapezius p. descendens: The S-EMG was significantly lower in resting than in working (Rest ↔ Work).

Table 14 Significant signed rank tests of the S-EMG parameters of the finger extensor, finger flexor and trapezius. The cells contain the conditions with the lower parameter (* p < 0.05; ** p < 0.01).

		mouse ↔ pen			s-click ↔ d-click	
	Rest↔Work	**AMS↔APS** s-click	**AMD↔APD** d-click	**BM↔BP** dr&dr	**AMS↔AMD** mouse	**APS↔APD** pen
Finger extensor						
$SEMG_{ext,rel}$	rest**			BP** (pen)	AMD** (d-click)	APD* (d-click)
$SEMG_{ext,cli}$	rest*			BP* (pen)	AMD* (d-click)	
Finger flexor						
$SEMG_{fle,rel}$	rest**				AMD** (d-click)	APD** (d-click)
$SEMG_{fle,cli}$	rest**	APS* (pen)		BM* (mouse)		APS* (s-click)
Trapezius p. descendens						
$SEMG_{tra,rel}$	rest**					
$SEMG_{tra,cli}$	rest**					

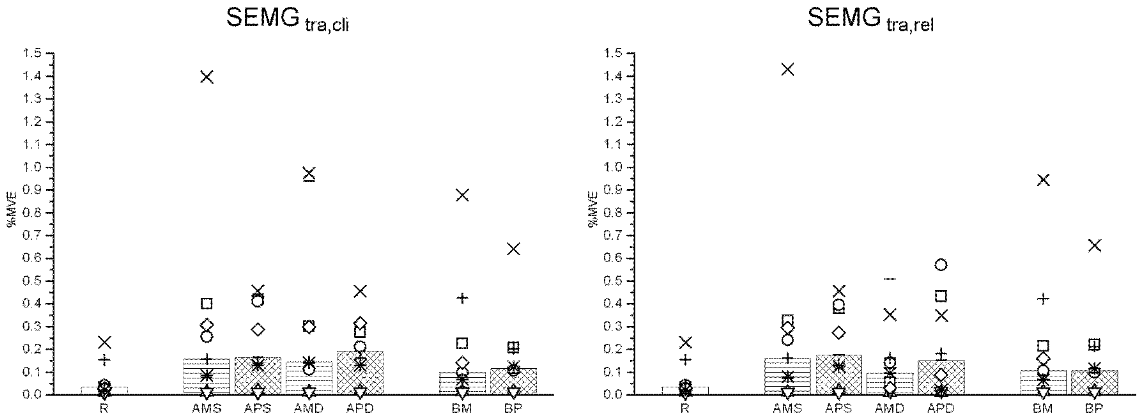


Figure 53 S-EMG in the trapezius during clicking ($SEMG_{tra,cli}$) and release ($SEMG_{tra,rel}$) (median and individual values)

8.3.5 I-EMG parameters

All I-EMG parameters were significantly lower in resting compared to working. In all other comparisons there were no significant differences between the conditions.

MUs were identified in 40 (out of 54) working trials and 13 (out of 27) resting trials. In subject 11, no MUs were found at all during work, but 11 during the three resting trials. In subjects 5 and 6, MUs were detected only in a few of the working trials (Table 15).

Table 15 Number of MUs (#MU) and number of MUs with at least 1000 action potentials ($\#MU_{1000}$) found per subject and task

	#MU										$\#MU_{1000}$									
Subj.	**0**	**2**	**5**	**6**	**7**	**8**	**9**	**11**	**12**	**Total**	**0**	**2**	**5**	**6**	**7**	**8**	**9**	**11**	**12**	**Total**
AMS	2	8	0	2	9	15	18	0	13	67	1	7	0	0	4	4	10	0	0	26
APS	2	11	0	0	12	4	1	0	7	37	1	8	0	0	6	1	1	0	1	18
AMD	6	9	0	0	17	5	12	0	14	63	2	4	0	0	7	2	1	0	3	19
APD	4	12	1	0	11	5	2	0	8	43	2	8	0	0	8	1	0	0	1	20
BM	12	10	0	13	14	11	16	0	11	87	2	4	0	8	4	7	4	0	2	31
BP	8	8	1	0	15	7	16	0	16	71	3	4	0	0	6	1	4	0	3	21
R	1.7	2.7	1.0	0	1.0	0	0	3.7	5.3	15.4	0	0	0	0	0.5	0	0	0.5	0	1.0
Total									**Total Mouse**	217									**Total Mouse**	76
Total									**Total Pen**	151									**Total Pen**	59

#MU and $\#MU_{1000}$: Tendentially fewer MUs (#MU) were found with the pen (Figure 54). The low levels of $\#MU_{1000}$ (number of MUs with at least 1000 action potentials), compared to #MU, show that many detected MUs were not very active. The box plots

suggest that during drag-and-drop tendentially more MUs were active than during single- or double-clicking.

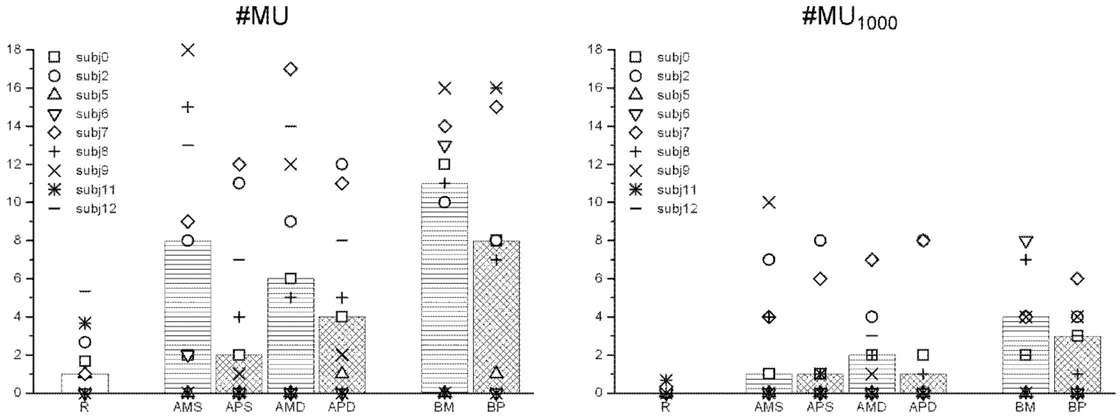


Figure 54 Number of MUs (#MU) and number of MUs with at least 1000 action potentials (#MU$_{1000}$) (median and individual values)

#MUAP and #DOUB: The ranges of the number of MUAPs (#MUAP) and doublets (#DOUB) were very large (Figure 55). Two subjects (2 and 7) had more than 20'000 MUAPs in most of the working tasks. The highest number was found in pen single-clicking (APS) in subject 2 with 51'000 MUAPs. With the mouse there were more doublets in single-clicking than in the double-clicking (although the number of MUAPs was higher in double-clicking). The quotient #DOUB/#MUAP reveals a very high percentage of doublets in many subjects of up to 37% (subject 0, BM). Four working trials with MUAP activity – all of them pen tasks – had a doublet rate of 0%. Only one subject had no doublets at all in all three resting trials (trials with MUAP activity).

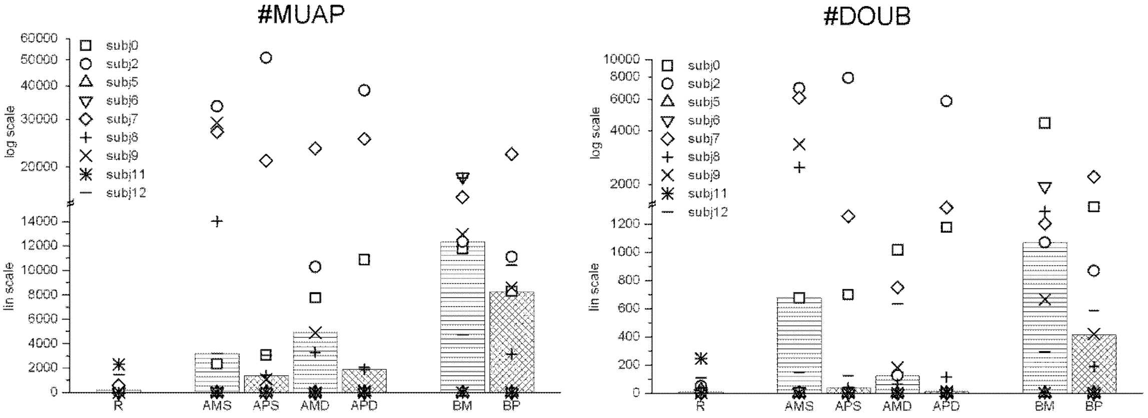


Figure 55 Total number of motor unit action potentials (#MUAP) and total number of doublets (#DOUB) (sum from all MUs; median and individual values)

#SIMU$_{mean}$ and #SIMU$_{max}$: Numbers of 8 simultaneously active MUs could be found in all working tasks (0).

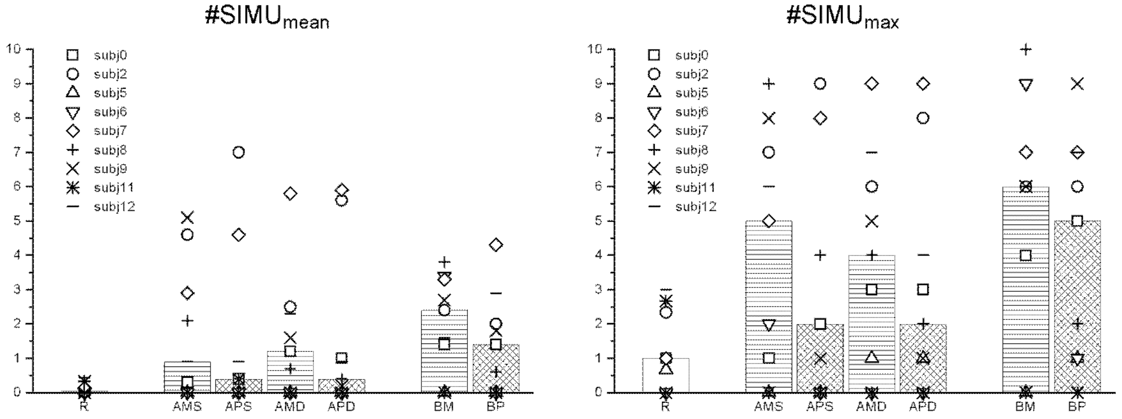


Figure 56 Mean and maximum number of simultaneously active MUs (#SIMU$_{mean}$ and #SIMU$_{max}$) (median and individual values)

%ACT: The activity found in resting was usually concentrated in distinct periods, often at the start or at the end, when the subjects may have had phases with incomplete relaxation or where they moved. The highest values during work were found in subjects 2 and 7. These had active MUs between 96 and 100% of the time in most tasks (Figure 57).

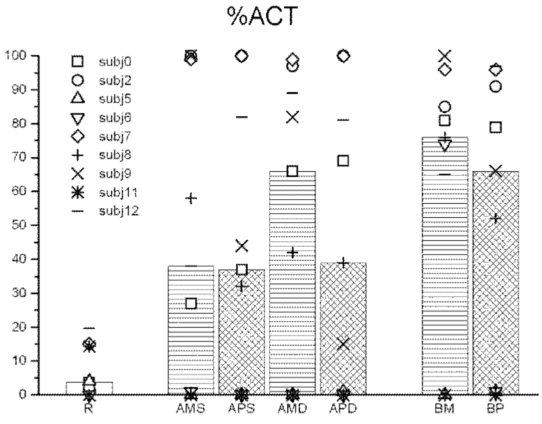


Figure 57 Percentage of time with at least one active MU (%ACT) (median and individual values)

#COMU: 18 continuously active MUs were identified, all of them in subj. 2 and 7 (except 1 MU in subj. 9), whereof 7 when using the mouse and 11 when using the pen (Table 16).

Table 16 Number of continuously active MUs (#COMU) per subject and task

Subj.	0	2	5	6	7	8	9	11	12	Total
AMS	0	2	0	0	1	0	0	0	0	3
APS	0	5	0	0	2	0	0	0	0	7
AMD	0	0	0	0	2	0	0	0	0	2
APD	0	2	0	0	2	0	0	0	0	4
BM	0	0	0	0	1	0	1	0	0	2
BP	0	0	0	0	0	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0
Total	Total Mouse									7
Total	Total Pen									11

8.3.6 Event-triggered S-EMG

In the event-triggered S-EMG superposition of the single- and double-click trials some cases were found with patterns that show a high trapezius co-activity and synchronisation with the clicking (Figure 58 (a)). Such elevated patterns were mainly found during mouse use (AMS and AMD). Most trials however, especially the pen trials, showed more stable patterns (Figure 58 (b), same subject).

In the event-triggered S-EMG superposition of the drag-and-drop trials, the standard deviation immediately after the click was increased, regardless of the pointing device, in about two out of three trials (Figure 59).

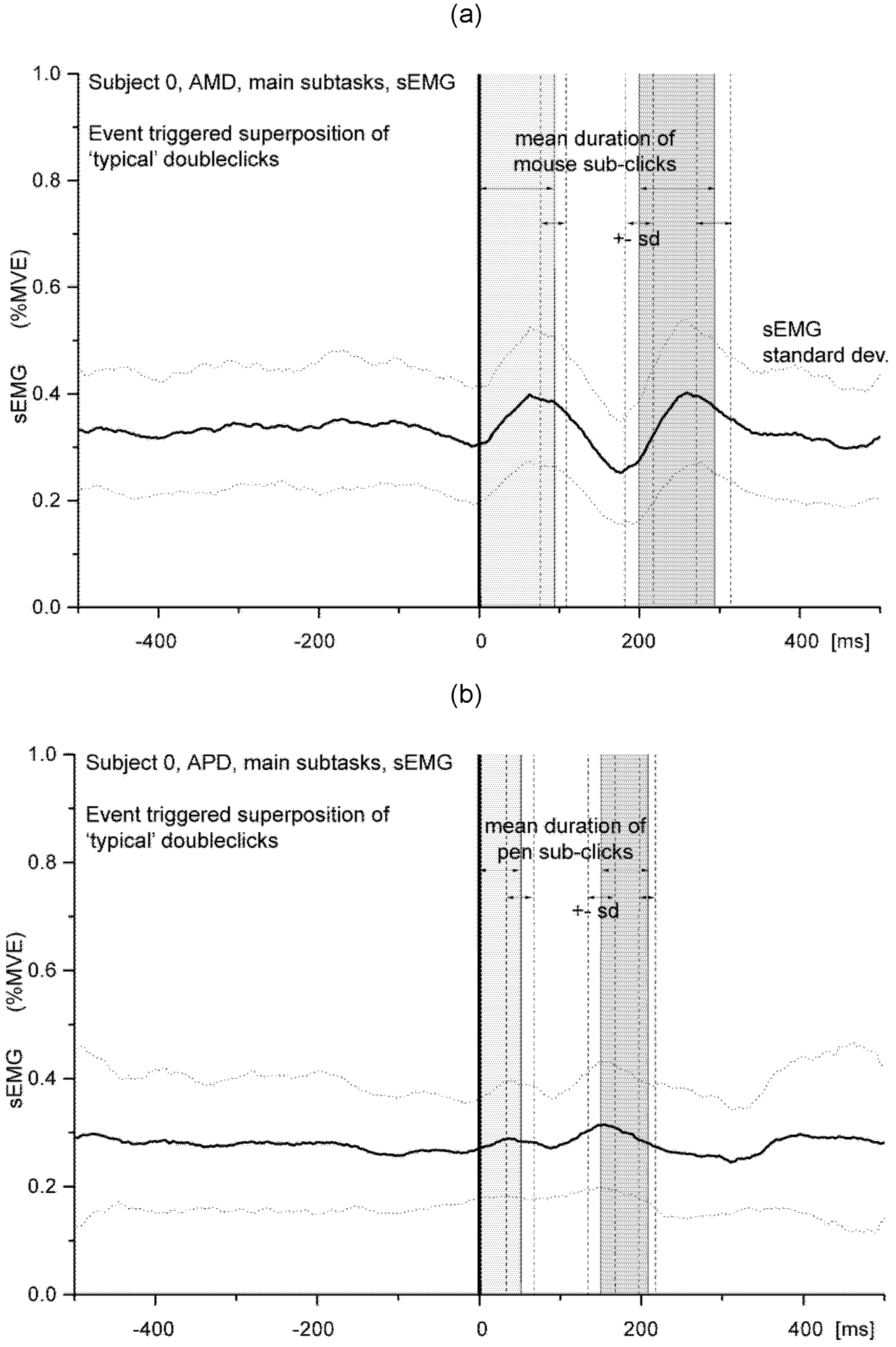


Figure 58 Examples of co-activity patterns during double-clicking in the trapezius S-EMG in event triggered superposition. (a) subject 0, mouse double-clicking (AMD), n=143; (b) subject 0, pen double-clicking (APD), n=178 (n=number of considered clicks).

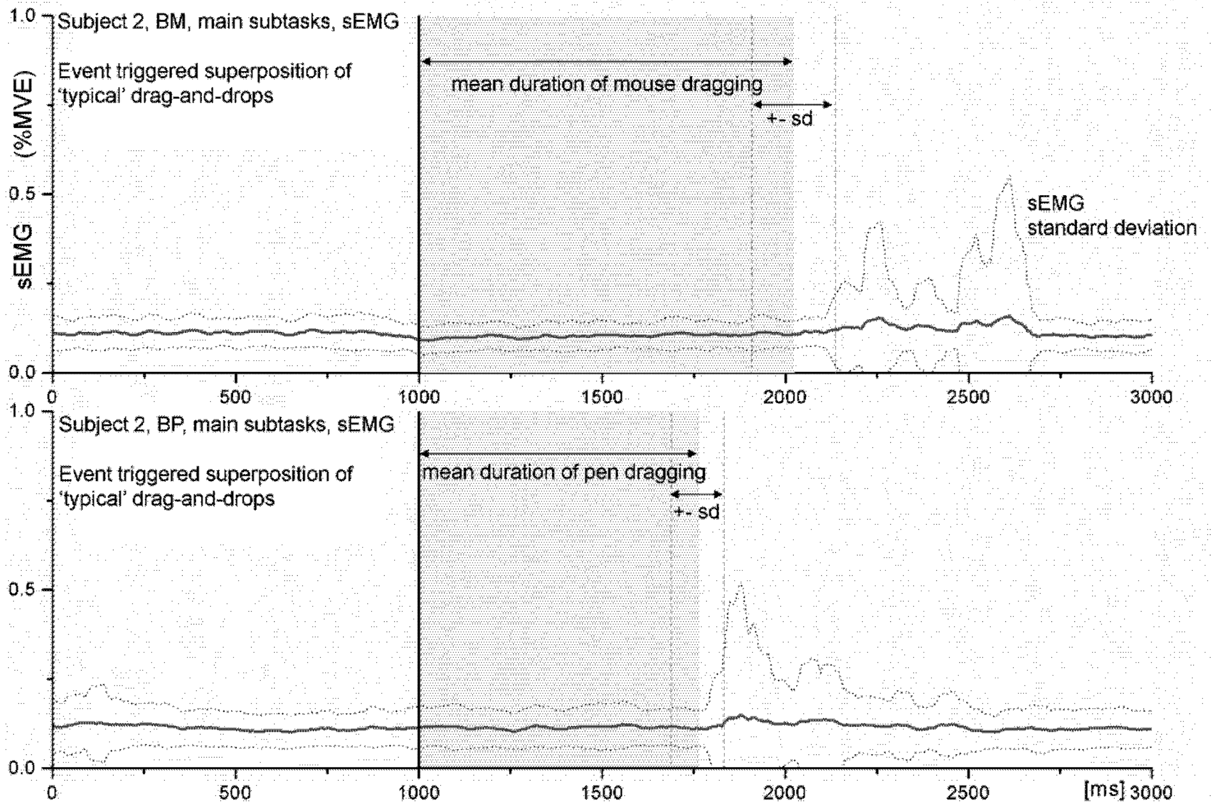


Figure 59 Examples of a co-activity patterns during drag-and-drop in the trapezius S-EMG in event triggered superposition (top: subject 2, mouse drag-and-drop (BM), n=74; bottom: subject 2, pen drag-and-drop (BP), n=111) (n=number of considered drag-and-drops)

8.3.7 Event-triggered I-EMG (cusum)

12 MUs met the given criteria (described in the procedures) with AMS (mouse single-clicking) (from 4 subjects), and 9 MUs with APS (pen single-clicking) (all MUs except one from the same subject). An example of a cusum plot is shown in Figure 60 (subject 2, AMS, MU3). The time course of this trial has been shown in Figure 49.

During pen single-clicking (APS) the significance limits of the cusum graph were surpassed less frequently than during mouse single-clicking (AMS). On average, a MU surpassed the upper limit during 63 ms in AMS and during 2 ms in APS. The upper limit was surpassed during 100 ms or more by 25% of the MUs during AMS and by 0 MUs during APS. For details see Table 17 and Table 18.

Firing rate increase can often be explained by a raise of the doublet rate. An interesting observation is that in subject 2 with AMS, the cusum graph (thus the firing rate) of all four MUs decreased shortly before and increased after the click (as in Figure 60).

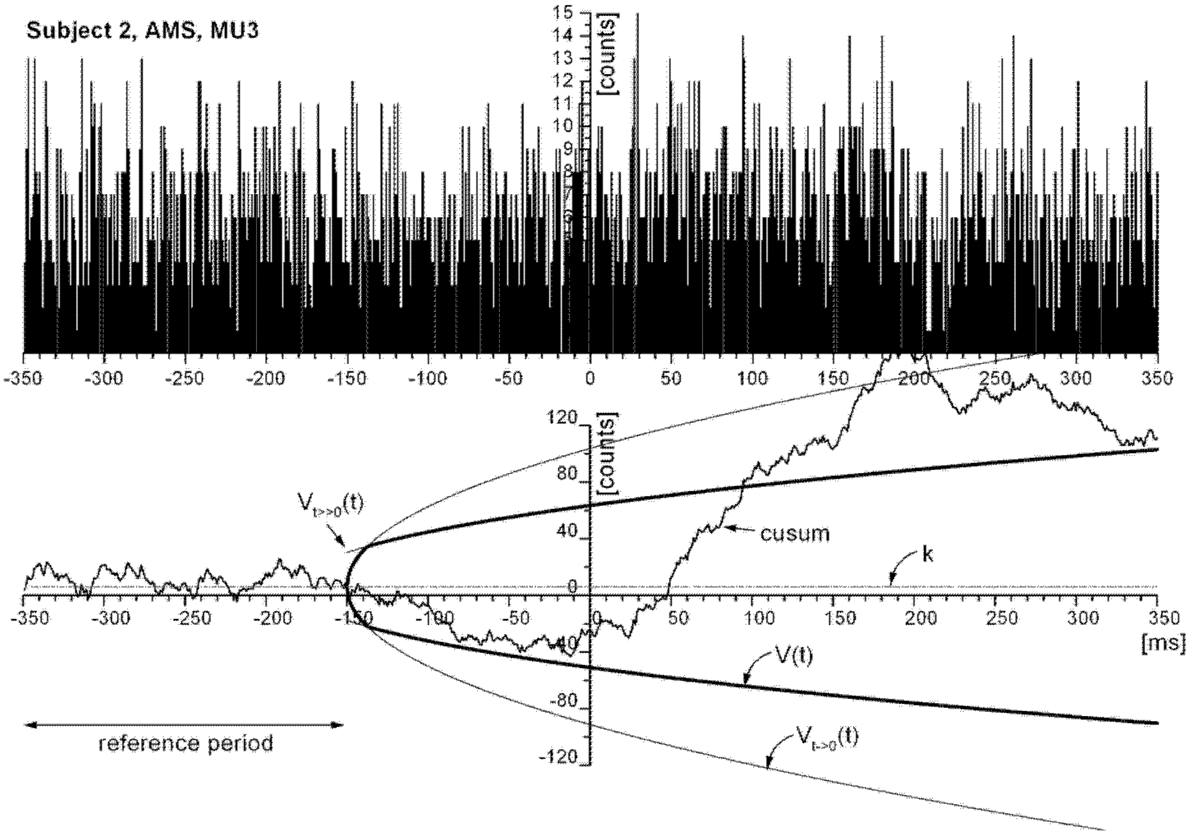


Figure 60 Example of a cusum graph (subj. 2, mouse single-clicking (AMS), MU3). Top: 1 ms bins of superimposed 700 ms-intervals of MU firings (click begin at t=0). Bottom: cusum graph. k = reference level = mean of reference period. $V(t) = \min(V_{t\to 0}(t), V_{t>>0}(t))$ = confidence interval. For details on cusum see 8.2.9.

Table 17 MUs included in the cusum analysis (overview)

= : cusum stays clearly within both significance limits
≈ : cusum surpasses limit(s) only slightly
↗ : cusum surpasses upper sign. limit during 100 ms or more
↘ : cusum surpasses lower sign. limit during 100 ms or more
n.r. : not reverting from limit surpassing

	AMS mouse, single-click	**APS** pen, single-click
=	3 MUs (25%)	5 MUs (56%)
≈	3 MUs (25%)	1 MUs (11%)
↗	3 MUs (25%)	0 MUs
↗ n.r.	2 MUs (17%)	0 MUs
↘	3 MUs (25%)	3 MUs (33%)
↘ n.r.	2 MUs (17%)	0 MUs
av. surpassing of upper limit	63 ms	2 ms
av. surpassing of lower limit	102 ms	34 ms

Table 18 MUs included in the cusum analysis (details)

AMS mouse, single-click			APS pen, single-click		
Subj	**MU**	**Behaviour**	**Subj**	**MU**	**Behaviour**
2	1	↗	2	1	↘
2	2	≈	2	2	=
2	3	↗ n.r.	2	3	↘
2	4	↗ n.r.	2	4	≈
7	3	↘ n.r.	2	5	=
7	4	≈	2	6	=
7	6	≈	2	7	=
8	2	=	2	8	=
8	3	=	7	5	↘
9	3	=			
9	4	↘			
9	10	↘ n.r.			

8.4 Discussion

8.4.1 Subjects, workplace and tasks

20 subjects were invited, 9 of whom were female and 11 male. After electrode insertion and signal quality checking, 5 female and 2 male persons had to be excluded either due to high electromagnetic noise or indisposition. The data of 4 additional subjects had to be excluded later because of EMG-LODEC misclassifications or previously unnoticed inability to double-click with the pen. Three of these latter subjects were females and one was a male. This way only one female remained in the nine analysed subjects. On top, the remaining female (subject 11) was the only subject where no active MUs could be found during work (but during rest). In a study concerning neck and upper limb disorders with computer work with 498 men and 785 women Tornqvist found a higher prevalence in females in all investigated body regions (Tornqvist et al 2001). In the neck the prevalence was twice as high in women as in men. Woods et al (2002) found that muscular activity in the forearm was higher in women, that they applied greater forces to the sides and buttons of the mouse and that they worked with more extreme postures of the wrist. The differences could be due to anthropometric diversity. The gender should therefore be a more important criterion when planning experiments on WRMD than in the present study.

Due to the small number of subjects, a careful choice of statistical methods was important. The analysis was limited to six comparisons: between resting and working; between using the mouse or the pen separately for singe-clicking, double-clicking, and drag-and-drop; and between single-clicking and double-clicking separately for mouse and pen.

Only non-parametric tests were used so that the reported p-values are reliable. Since the six comparisons belong to independent research questions, the computed p-values can be considered relevant and an adaptation due to multiple comparisons is not justified. Nevertheless, isolated significant outcomes were not considered.

The tasks were chosen so as to ensure a certain validity regarding real life settings but still allowing enough control in the laboratory. They were built up of monotonous, main subtasks (5 x 1 min.), interrupted by different, less monotonous subtasks with varying visual and motor demands. Where possible, the analysis was conducted only on the main, controllable subtask (performance and S-EMG). Effort, pain and I-EMG could however only be conducted on the whole signals.

The Compaq M-SF 14-2 mouse was chosen because of its simple and ergonomically non-optimised design. Different approaches to reduce strain have been undertaken in the history of mouse design, but often the ergonomic improvement of one factor resulted in the deterioration of other factors.

The pen was chosen with a tablet with an active area of only 127 x 93 mm. Larger tablets would be impractical when placed next to the keyboard of a normal office workplace. But even with such a small area, mapping the screen proportionally, the accuracy attained is very high. As the distances are short, the small area is beneficial to the performance and to the range that can be reached without the involvement of arm movements. This should result in less strain to wrist and shoulder.

No issues with environmental electromagnetic noise were encountered during the preliminary tests. After successful measurements with a couple of subjects however, electromagnetic noise reached levels so high that the measurements could no longer be carried out. The equipment was then transferred to a shielded room several floors below ground where the experiments were finished with the remaining subjects without electromagnetic problems.

8.4.2 Performance

If the operation of an input device causes strain, and that operation time can be reduced, then the user is exposed to the strain during less time. For this reason, performance measurements were performed. Also, if an alternative input device is found to be ergonomically superior to the mouse and, additionally, increases performance, then the individual might consider substituting the mouse *before* the occurrence of irreversible WRMD.

Working with the pen was significantly faster and required shorter depressing time in half of the mouse/pen comparisons. In the other mouse/pen comparisons, the trend was also for the pen to be faster. Not surprisingly, single-clicking was significantly faster than double-clicking.

Even with only half an hour of pen experience attained a day or two before the experiment, compared to years of practice with the mouse, most subjects achieved a better performance with the latter, i.e. the number of clicks per time was higher, and the average depressing time was shorter. Performance losses arose a) with the 'pen' pointing mode, in that the subjects were not used to the direct mapping between screen and tablet and sometimes tried to pick and roll the pointer with multiple moves as with a mouse, and b) with double-clicking, in that they sometimes did not hit twice the same spot exactly enough, mostly due to grabbing the pen with too flat an angle. Two subjects had to be excluded from analysis for that latter reason. Their training had apparently been insufficient. Double-clicking could alternatively have been achieved with the pen's lateral (double-)switch, which was however not permitted in this experiment in order to have comparable results with the mouse. In a study with regular pen users, the performance gain would probably be even more considerable.

From own observation it can be said that people tend to install a pen only after they have developed serious WRMD that prevent them from further working with the mouse. Most other people trying out the pen can't operate it intuitively and give up quickly. People trying out a trackball, e.g., are familiar with it more rapidly and therefore more likely disposed to integrate it. Training is thus crucial; 30 or 60 minutes seem already to be sufficient. What should make the decision to switch to a pen easier is that it can be used together with an existing mouse (USB plugging). It is a good idea to keep the mouse and place it, e.g., to the left of the keyboard. There are also pen models that come with an additional cordless mouse that can be operated on the tablet.

A possible performance cutback of the pen is that it has to be grabbed each time when alternating between keyboard and pen. On the other hand, switching from keyboard to mouse creates a certain performance loss as well, because the pointer has to be found on the screen. This is typically done by quickly swaying the mouse back and forth during a second or so. With the pen, the pointer positioning is absolute and there is no need to search the actual pointer position.

8.4.3 Effort and pain

With the pen, the subjects reported less effort during single-clicking than with the mouse in all investigated body regions (hand, forearm, neck). The median effort in the forearm, e.g., was 3.5 on the Borg scale with the mouse and 0.0 with the pen (only one subject indicated more than 0.5). With double-clicking, the pen put significantly less effort to the hand and forearm, but was indifferent in the neck. The self reported effort confirms the assumption that the adverse effects from constrained postures observed with the mouse, i.e. permanent wrist and finger extension, forearm pronation and ulnar deviation, will be diminished with the pen.

Single- and double-clicking however was not rated differently. The expected higher effort with double-clicking could not be demonstrated, and the tendency was even that double-clicking caused less effort in the forearm when working with the mouse. Maybe this was due to the slower performance at double-clicking. With the pen, double-clicking was tendentially rated worse, but many subjects had difficulties with double-clicking because of too little training as mentioned above.

Neck pain was not rated significantly reduced while resting. It might be explained by the presence of the intramuscular electrodes. Pain in the other regions (hand, forearm, upper arm and shoulder) was mostly zero. 20 ratings (out of 108) were greater than zero with the mouse and 8 with the pen. This suggests again that the forearm and hand postures assumed with the pen were less strenuous than those assumed with the mouse.

8.4.4 Muscle activity of the finger muscles

S-EMG values of the finger muscles were always significantly lower during resting. In some comparisons between mouse and pen, the pen caused significantly lower activity in the finger extensor and flexor. However this result should be viewed with care, as i) different muscles are mobilised with the two devices, and ii) the skin with the attached electrodes may be shifted in relation to the underlying muscles when changing between pronated (mouse) and neutral (pen) hand position.

In the single-/double-clicking comparisons with the mouse, the values were mostly significantly lower with double-clicking, except for the finger flexor during the click. This contradicts the assumption that double-clicking would induce more activity in both antagonists and may be explained by the lower performance with fewer mouse movements.

In the single-/double-clicking comparisons with the pen, the values were significantly higher with double-clicking in the finger flexor during the click. Presumably the pen was grabbed stronger in order to hit the target twice within the given proximity of a few pixels. The finger extensor activity, while not touching the pad, was significantly lower with double- than with single-clicking, which may again be explained by the reduced overall activity due to the lower performance and fewer movements on the tablet.

Regardless of the question if double-clicks cause ‘extra’ activity (e.g. doublets), a double-click induces finger activity and possibly trapezius co-activity during twice the time as a single-click (see graph in Figure 58 (a)).

Although no systematical posture analysis was included, forearm pronation, ulnar deviation, wrist extension, finger extension and finger abduction should all be reduced with the pen, because the pen is grasped and operated with a more neutral hand posture.

8.4.5 Muscle activity of the trapezius muscle

All surface and I-EMG values of the trapezius muscle were significantly lower while resting. No other significant results could be found in the EMG. Most I-EMG parameters were however tendentially lower with the pen.

As in the previous experiments, surface (and most intramuscular) EMG differences between the subjects were very high. Two subjects (5 and 6) had lower values during work than most others had during rest, and no active MUs in 13 out of 18 trials. This confirms the findings of previous experiments that the same task can be executed with high or almost no trapezius muscle activity.

Number of MUs: EMG-LODEC was used in automatic mode with no user intervention. This turned out not to be too reliable, as MUs were often classified as new ones after firing breaks. More user intervention (adjusting certain classification limits or merging similar MUs by hand) should have reduced results with unrealistically high numbers of MUs of up to 50. Two measurements had to be completely excluded for this reason. In the other measurements it is still possible that some MUs were not reliably merged. The parameter #MU (number of identified MUs) might therefore be too high, and #COMU (constantly active MUs) too low.

Active MUs (with a simultaneous raise of the S-EMG) were sometimes found during rest. However it cannot be concluded that these subjects were not able to relax, because the observed activity occurred usually in blocks at the begin or end of the rest, maybe due to some disturbance. Nevertheless there were observations of prolonged muscle activity in resting, however only rarely.

'Cinderella' units: 7 continuously active MUs were seen in mouse and 11 in pen trials, mainly in two subjects (2 and 7). In one of these trials (pen single-clicking, subject 2) as much as 5 MUs were constantly and simultaneously active. 9 minutes of activity is still far from a whole working day, but it should encourage to continue research with longer recordings to conclusively prove Hägg's hypothesis.

Doublets: In some subjects, several thousands of double discharges were found in the nine minutes of a recording. The highest rates in relation to the total number of discharges (up to 37%) were not found in double-clicking, but mainly in mouse single-clicking trials (3 in AMS (mouse single-clicking), 1 in BM (mouse drag-and-drop), and 1 in APS (pen single-clicking)). Only in 4 of the working tasks no doublets were found at all, all of which were pen tasks. In a controlled setting with no arm movement, Olsen et al (2001) found doublets in the right trapezius muscle during left- and right-hand double-clicking strongly correlated with the clicks. One of their MUs was only activated with doublets. Sjøgaard et al (2001) studied doublets in the m. extensor digitorum communis during double-clicking and found doublets at a rate of 10% of all interfiring intervals, the majority of which during the high-acceleration phase between the two partial clicks. This rate was reduced to less than 1% when performing ramp contractions. Their conclusion that double-clicking causes elevated doublet rates in the finger extensor muscle can be extended with the present findings to elevated rates also in the co-activated trapezius muscle, induced also with single-clicking or drag-and-drop. In our study the doublets were not investigated in respect to a singular click and the smaller number of doublets in double-clicking, compared to single-clicking, may be due to the lower overall performance.

In contrast to the sometimes bad merging of MUs after longer breaks in dynamic tasks (in automated mode), the programme worked reliably in the short-term recognition of MUs, as Zennaro et al (2003) could show. As an example illustrating the high doublet rate, a 200 ms clip is shown in Figure 61 with a typical occurrence of two doublets of the same MU (MU6) within short time.

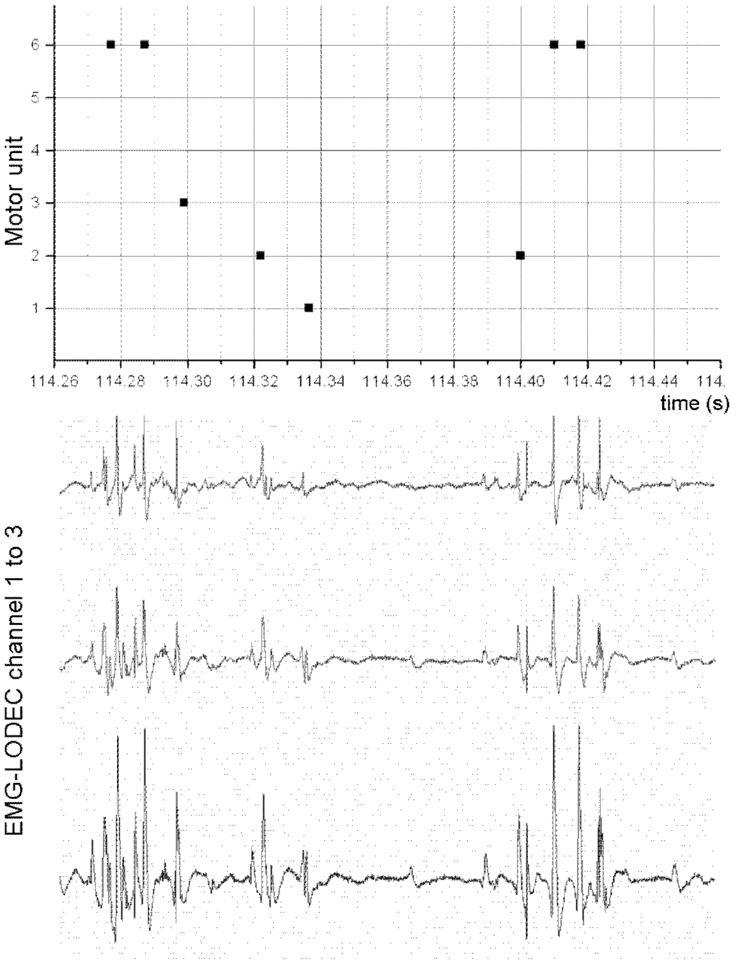


Figure 61 Example of two doublets of the same MU within less than 200 ms, and the EMG-LODEC signal trail. High doublet rates were found in many trials.

8.4.6 Event triggered S-EMG

The superposition of signal intervals from the trapezius S-EMG, aligned at the click begin, revealed elevated patterns with temporal correspondence to the click in some mouse trials. The respective patterns in pen trials were much less eminent (Figure 58). In the majority of subjects such elevated patterns were not seen. This demonstrates again that co-activity occurs in some persons, while others are not susceptible, and that a pen may reduce the risk. Figure 58 shows another point to consider: If dynamic co-activity occurs with a mouse click, then a double-click could evoke the same activity twice. Also, a shorter activation time (as with the pen in the bottom figure) would co-activate the muscle during less time.

The increase of the standard deviation after drag-and-drop (Figure 59) can be explained by the vertical, top-down arrangement of the objects in the main subtask. The arm had to be pulled back regularly after some movements. The two peaks seen in the mouse and the single peak in the pen task suggest that this happened with two different strategies.

8.4.7 Event triggered I-EMG (cusum)

The event triggered I-EMG of subject 2 demonstrates that dynamic co-activity can be present in the trapezius muscle during clicking with the mouse. 3 of the 4 MUs that were detected in subj. 2 during mouse-clicking show a MUAP increase, with their cusum graph surpassing the upper significance limit during more than 100 ms. The MU activity was reduced shortly before the click and raised after the click begin, which is an exact image of what the finger extensor does. With the pen, no upper limit surpassings could be observed.

These findings are valid for the subject under investigation and the specific electrode location. It can’t be concluded that they are representative for the whole muscle. Co-activated MUs could be described only in a few subjects. It can’t be concluded if this is a rare or frequent occurrence and what the chances are to encounter this in a specific registration and recording location. Zennaro et al (2003), registering I-EMG simultaneously from two locations in the trapezius muscle 2 cm apart, found very different MUs and firing patterns in the two locations.

There were also MUs with activity decreases that fell below the lower significance limit and were not followed by a later raise. This could be a consequence from a temporary release from a strenuous constant finger extension, reflected in the trapezius muscle.

8.4.8 Conclusions

The difference of all measured and perceived parameters between work and rest is so substantial that the importance of work breaks must be stressed once again.

A pen, replacing the mouse, can reduce the effort in the neck and especially in the forearm and hand. At the same time it can increase performance in click-intensive tasks.

Dynamic co-activity of the trapezius muscle can arise in susceptible persons with computer work. It can be attributed to an increased firing of single MUs which may or may not be visible in the S-EMG. S-EMG is thus not always an adequate method to detect hazardous trapezius co-activity.

Persons using a mouse seem to be affected more by dynamic co-activity than those using a pen. Continuous MU activity may arise regardless of the choice of pointing device (demonstrated in this experiment for 9 minutes). Breaks are thus crucial even without perceived effort (pen users reported often to perceive no effort) in order to avoid damages due to overuse of single MUs.

Presence of trapezius co-activity during computer work has been shown before. However to our knowledge this is the first study to demonstrate temporal relationship of MU firing with mouse clicking.

9 Concluding Discussion

This thesis aimed at attaining a better understanding why muscle strain develops in human computer interaction. The experiments ranged from performing simple finger tapping tasks, improving the knowledge about muscle coordination, to an application-oriented comparison of mouse and pen. The various methods extended from standard surface EMG to event-triggered intramuscular EMG techniques. It turned out that the muscles of the fingers, hand, arm and neck are not acting independently but rather as an entity, and that the neck experiences strain not only from postural adaptation, but also because there is static and dynamic co-activation with keyboard and mouse operation. It could also be shown that the perceived effort can be reduced in experienced mouse users when they try a pen, while at the same time performance is increased. Possible explanations for co-activity and consequences are discussed in this last chapter.

9.1 Experimental design

The experiments started with constrained tasks and expanded to tasks with reduced control, that were however closer to real-life. The freedom in the OPT condition of the first experiment to chose one's personally preferred tapping rate revealed that people favoured very different work paces. The self determined tapping rate was related to relatively low muscle activity, which is the reason why it was decided not to constrain the working speed in the more ergonomically oriented following experiments, and to include the performance as an independent parameter. In the last experiment the structured work was intermixed with self-paced 'subtasks' with a certain 'fun factor' (such as puzzles), offering variation to prevent monotony. Although monotonous, controlled tasks would be easier to analyse, the validity of the outcomes for daily work may be doubtful.

This proceeding was successful. The trapezius muscle could be investigated well with respect to a singular clicking movement.

9.2 Methods

The musculoskeletal system is very complex, so that only exemplary muscles were chosen for the studies. Because of clinical relevance, and good accessibility, the focus was set on the trapezius muscle. The surface EMG qualified well to describe the interplay of muscles, but it failed to predict the moment of exhaustion which led to aborting the tapping task.

With intramuscular EMG, detailed information on the control of muscle activity could be gained. Intramuscular EMG methods were successfully adopted to demonstrate the modulation of the firing rate of a single trapezius motor unit (MU) in dependence of the finger movement. The methods did successfully describe ongoing activity of single MUs ('Cinderella behaviour'). The reliability of the intramuscular EMG methods was confirmed by Zennaro et al (2003). But although valid information on single MU activity could be described, it should be considered that intramuscular EMG does provide exemplary information only at the specific electrode site, and that this information is not representative for the whole muscle.

Current EMG methods do not allow to distinguish between muscle load and overload. Developing EMG methods so that they can be used to predict situations that cause muscular overload would be an important research field for the future for a health based work design.

9.3 Results and conclusions

In the control conditions, total trapezius muscle relaxation as measured by surface EMG was achieved only by a part of the subjects, while others maintained some activity during a certain time or even during the whole resting condition. The differences between the subjects were considerable. Statistically however the activity in resting was significantly reduced, compared to working, in all experiments. Intramuscular EMG did not show MUs active continuously during the entire resting condition. Pain was not the reason for the inability of some subjects to relax, as only pain-free subjects have been invited; a relationship between disorders and the ability to relax was not investigated.

A relationship between tapping force and tapping rate was not found, even though increased speed means increased acceleration and finger muscle activity, which was documented. This means that measurements of external force cannot be used to deduce the internal load. In the long-term tapping task, it was not possible to predict the moment of abortion due to exhaustion, based on level, constancy, or kind of muscle activity. Apparently motivational factors were more decisive to stop the trial than the registered parameters.

The analysis of finger activity confirmed Weiss' finding (1998) that increased tapping speed leads to increased muscle load because of the switch from co-operative to competitive antagonism of the finger muscles. Lower muscle activity was found in the clinically relevant trapezius and finger extensor muscles when the subjects assumed a slightly reclined body posture. This significant effect lets assume that the head posture is relevant for the basic muscle tone in human computer interaction.

In experiment 2 using intramuscular wire electrodes, pain was minimal initially. After three minutes of tapping, a moderate increase was observed in the arm and hand. Despite optimal ergonomic conditions, continuous activity of a MU was shown in three subjects during the whole recording period (three minutes) of tapping or data inputting. The applied methods of intramuscular EMG analysis proved to be practical, so that the third experiment comparing mouse and pen could be started.

In the third experiment it turned out that the pen caused less perceived effort and at the same time higher performance, despite the minimal time of familiarisation. This shows the unused optimisation potential in human computer interaction. Single-clicking did not cause less effort, but the performance was higher than with double-clicking. As no significant differences were found in the surface and intramuscular EMG between mouse and pen and between single- and double-clicks, the performance gain did apparently not increase muscle load.

The mouse/pen comparisons were realised with an ergonomically optimal posture which caused almost zero trapezius activity (as measured by surface EMG) in some subjects. Average surface EMG levels were in the range of 0.1 to 0.2% MVE and did not differ between the periods of clicking and release.

Despite these low surface EMG levels, some MUs with more than 1000 action potentials were found in 7 of the 9 subjects and in amounts between 10 and 35 MUs in each one of them. Many measurements included remarkably high numbers of doublets, not only during double-clicking as previously described by Olsen et al (2001), but also during single-clicking or drag-and-drop. Doublets are provided by the nervous system to optimise fast force or velocity increase (Søgaard et al, 2001). Also, after a doublet, the force level of a MU remains elevated despite a lower firing frequency. This is apparently a mechanism of the body especially used to maintain the working capacity of fatigued fibres (Griffin et al 1998). However, as Søgaard et al further describe, doublets lead to Ca^{2+} accumulation within the muscle cell, which will eventually cause cell membrane breakdown and lead to muscle fibre necrosis.

Sjøgaard et al (2001) explained their high doublet rate findings in the m. extensor digitorum communis with their identified MUs being mainly of type I with slow contraction properties. The need for fast contraction in double-clicking could only be met by these if implementing special motor control patterns. The proportion of activated fibre types has not been investigated in our trapezius muscle studies, but assuming a high type I proportion in this postural muscle, this could explain doublet rates of up to 37%. This might even be a hint to why strength training is often reported to reduce WRMD in the neck (Jordan et al, 1998; Ahlgren et al, 2001; Waling et al 2002), as muscle hypertrophy happens, among other, by a proportional increase of the number (and size) of type II fibres (Kadi et al, 2000). The pain reduction would in that case not be achieved by less co-activity, but by type II fibres, which are less prone to doublet firings, taking over the co-activity.

The connection between finger movement and trapezius muscle activity was further investigated by event-triggered superpositioning. This revealed a significant modulation of the surface EMG signal in relation to the clicking. In event-triggered intramuscular EMG, several MUs could be found whose recruitment pattern was modulated by the clicking. This proved dynamic co-activity and a strong relationship between finger movement and the activity level of distinct MUs of the trapezius.

If ongoing activity of single MUs leads to muscle fibre degeneration, the overall level of muscle activity (by surface EMG) is not of relevance. Still, reduced ‘gaps’ in the surface EMG may show a reduced MU substitution. Westgaard et al (2001) described high prevalence of shoulder and neck pain despite minimal static trapezius EMG activity (<1% MVE) during day-long measurements in service workers.

The relaxation of the trapezius muscle may also depend on visual demands: Blangsted et al (2003) demonstrated a close relationship between trapezius and facial muscle activity. Because of the development and innervation of the trapezius muscle being different from that of the other somatic skeletal muscles in that the trapezius muscle belongs closely to the facial muscles, the trapezius motor control may be closely related to hand-eye coordination. The relaxation may thus depend on tasks requiring less visual demands than those in computer work.

Upper extremity pain may also be included in the mechanism of disorder generation, as described by Schulte et al (2004), who experimentally induced pain to the biceps, which led to increased trapezius activity.

We have seen that the muscle is probably not overstrained in terms of not being able to meet the required force demands, but the neuromuscular control strategies do not protect single MUs from overload. The system was apparently not designed to fit today’s particular needs with human computer interaction. Approaches should be made on two ends: adapting the human-computer interfaces such that they better meet the body’s neuro-/motophysiological capability and capacity, and learning to utilize one’s physiological capabilities the best possible way when confronted with unsatisfactory conditions that can’t be altered.

The portrayed unhealthy motor patterns must be seen within a wider context of undeveloped, or poorly developed motor behaviour that most ‘civilised’ adults are concerned of. We are using our bodies in a most inefficient way, lost body awareness and are not able to integrate subsidiary muscles in the movements. Sitting immobile and constrained in the office chair, e.g., we tend to use only some muscles of the shoulder girdle and some cervical vertebrae to rotate the head or move it up and down; instead, the integrative use of the strong muscles of the back and the inclusion of all the vertebrae would allow smoother and more effective movements, taking away the strain on the shoulder girdle.

Moshe Feldenkrais (1904–1984) developed a method for neuromuscular re-education through sensory-motor awareness. He believed that the cause of repeated injury, many pains and movement restrictions was predominantly the result of poor habitual use of oneself, brought about from half-learnt or badly learnt movement patterns which constrain us to a small portion of our potential. The Feldenkrais method is believed to stimulate the plastic properties of the nervous system and to explore and fill in gaps and missing links in a person’s neuromuscular self-image. Among other, it emphasises the inclusion of those body parts persons have never before considered in their image of movement, giving them an intimate knowledge of the complex relationships between their body parts so that they can experience how the whole of themselves cooperates in any movement, and providing new functional motor patterns by increasing awareness of tense muscles that can be released, and increasing tonus in muscles which could not formerly be used or differentiated (Lyttle 1997). Feldenkrais spoke of immature vs. mature behaviour and saw the origin and adoptation of physical and psychological patterns in personal history, upbringing, culture, injuries, illness, etc. These patterns are deeply embedded in our nervous system, and often become outmoded or dysfunctional, creating unnecessary physical, and psychological limitations. In his method, Feldenkrais uses organic learning, movement, and sensing to free us from habitual patterns and allow for new patterns of thinking, moving and feeling to emerge. He synthesised insights from physics, motor development, biomechanics, psychology, and martial arts to develop a powerful, effective, and practical application, demonstrating the inseperableness of thought, feeling, perception and action.

A randomised controlled trial of physiotherapy and Feldenkrais interventions during 16 weeks in 97 female workers with neck-shoulder complaints reported indeed significant positive changes in complaints after the Feldenkrais intervention, but not after the physiotherapy intervention (Lundblad et al 1999). Nevertheless, the Feldenkrais method has been found not to benefit all persons (Lyttle 1997). Awareness is central to the method, and people’s potential for this varies. It has limited success for patients who want a quick fix by having something done to them, without participation on their part.

Ebert (1996) speaks of ‘co-movements’ as occurrences with undifferentiated, not fully learnt movements, indicating a general motor activity and a nervous propagation in the entire motor system. These co-movements are not provoked biomechanically, but through central nervous connections. Eliminating all superfluous and partial activity, an economic and coordinated movement is formed by and by. Nikolai Bernstein (1896-1966), one of the founders of the area now defined as motor control and a significant contributor to the structure-function controversy, identified three phases of motor learning (in: Russell 1999, pp 77-78): In the first phase, most degrees of freedom are blocked. This makes a new movement possible, though still clumsy. A child learning to write an O, e.g., does not make use of the many joints of the fingers and hand, but starts by writing the O out of the shoulder, stiffening most other joints. In the second phase, all potential degrees of freedom are integrated into a complex and exactly coordinated pattern. The child starts using the blocked joints, resulting in much smoother outcomes. In the third phase, the movement is economised by integrating the reactive forces (gravity, elasticity of muscles and tendons, friction etc.) and eliminating unnecessary contractions. This will make the movement even smoother and above all easier. The co-activity observed in our experiments may be seen as a deficiency occurring at this third phase. Weiss’ claim (1998) that ergonomic design should aim at minimising the physical costs in the sense of total muscular metabolism should be extended to a more comprehensive concept, focusing on the minimisation of degenerative effects by way of modeling the movements of human-computer interaction the most coordinative, effortless and smooth manner possible, endorsing the force development from the limbs on the larger, stronger muscles.

Altogether, the conducted studies provide evidence that co-activity and unfavourable MU patterns of the trapezius muscle can occur in human-computer interaction, and that phases with complete muscle relaxation are important in the prevention of work related musculoskeletal disorders. Further research has to compare the occurrences of unfavourable motor activity in persons with and without WRMD. Because of the randomness of detecting such specific patterns, a large collective will be needed.

9.4 Recommendations

The PROCID research group (see 2.4) found ongoing activity of single MUs under a wide variety of conditions, taking into account physical load, movement patterns and psychological stress during work. The group could summarise the outcomes to six recommendations, which are given in Table 19.

Table 19 Recommendations of the PROCID group for healthier computer work (Sandsjö et al 2001)

	Recommendation	Risk Factor
1	Operators must limit repetitive finger movements and constrained postures. There must be a selection of input devices including possibilities for non-hand input alternatives.	Fast repetitive finger movements trigger co-activity in neck and upper limb muscles. Lack of variation in activation of motor-units.[i]
2	Operators must avoid double clicking.	Fast motor unit firing induces peak muscle load.[ii]
3	Operators with pain should not just switch mouse hand to avoid the pain, but should make use also of other input alternatives.	Contralateral activity may occur.[iii]
4	Breaks from computer work must be frequent and allow for mental relaxation. Operators must be educated how to achieve full mental and muscular relaxation.	Lack of motor unit silence during work. Mental load activates the same motor-units, as does computer operation.[iv]
5	Operators must be qualified to fit the tasks to their ability and pay attention to signs of fatigue, pain and/or discomfort. Employers must be alert to such reporting and take actions - for instance by introducing technical and/or organisational changes.	Pain/discomfort and/or fatigue do not in itself prevent muscle activity.[v]
6	Employers and operators must pay attention to factors contributing to stress in the work situation and take actions to limit stress.	Mental load, distress and/or time pressure increase muscle activity.[vi]

Reported in:

[i] Rissén et al (2000); Sandsjö et al (2000); Schnoz et al (1999, 2000); Sjøgaard et al (2000)

[ii] Sjøgaard et al (2001); Søgaard et al (2001)

[iii] Søgaard et al (2001)

[iv] Birch et al (2000); Jensen et al (2000); Forsman et al (1998, 2000, 2002); Kadefors et al (1999); Kitahara et al (2000); Søgaard et al (2001); Thorn et al (2002)

[v] Birch et al (2000); Lundberg et al (1999); Rissén et al (2000); Sandsjö et al (2000); Sjøgaard et al (2000)

[vi] Lundberg et al (1999); Rissén et al (2000); Sandsjö et al (2000); Sjøgaard et al (2000)

The findings included in this thesis support these recommendations. The following list of personal suggestions, deducted from experiments, literature, and own experience, may help individuals using computers intensively to prevent, or alleviate, disorders and pain:

Input devices

- Try out alternative input devices, play with them, use them intensively for several days, sense exactly how your body reacts. Check how far from ‘neutral’ the devices force your limbs, feel if they cause permanent strain (permanent strain will eventually lead to pain). Arrange with your vendor to test a variety of pointing device or keyboard alternatives before you decide for one.

- Don't put too much trust in labels like 'ergonomic design', 'natural shape' etc. Don't let yourself seduce by nicely curved mouse shapes pretending 'perfect fit to your hand' etc. Often the reduction of one strain factor is followed by the increase of another one. Again, try out, and trust your experience.

- Your health is worth a financial investment – however 'more expensive' does not always mean 'better'.

- An 'ergonomic' keyboard may be beneficial in that it turns your hands to a more neutral base position, but people tend to respond to them very individually. Make sure it's not too broad, forcing your mouse and right hand too much to the right – the lever principle would cause additional load to the right shoulder.

- Avoid using a notebook keyboard for extended periods. If possible use an external keyboard and pointing device. Consider an external display as well, as the extra keyboard will increase the distance between your eyes and the laptop display.

- Gel-filled wrist supports for the keyboard and mouse may reduce strain from desk or laptop edges or permanent wrist extension. Avoid wearing a watch during work.

- Device designers should create ambidextrous devices. Also, these should be available in a range of sizes.

- Joysticks may reduce some of the strain, while bringing up implications with precision and ongoing co-contraction of antagonistic muscles.

- Laptop touchpads and track-point mice should not be used for extended periods.

- The pen is a good alternative to the mouse. It has experimentally proven to cause less effort and increase performance. Invest an hour to learn its proper operation.

- Most present-day computers can be used with two (or more) pointing devices plugged in simultaneously. Keeping your standard mouse and placing it to the left of the keyboard, e.g., is a good idea when installing an alternative device.

- Switching the mouse hand can be an idea for pain reduction on short-term. Don't make this a permanent solution however, as the pain could spread to the other arm and you could end up with pain on both sides.

- If using a mouse, make sure it's moving smoothly. A sticky mouse is not only annoying, but will produce a lot of stress and strain. A light-operated mouse is superior in this respect to one equipped with a ball. If it is operable without a mouse mat, it can be repositioned easily further away from, or closer to the body, or when switching the hand. If using a mouse with a ball, clean the mechanical parts regularly.

- Don't hold the mouse, and don’t hover the fingers over the keyboard when you don't have to. Try to lay your index finger on the scroll-wheel or some other non-active area when you’re not clicking in order to avoid permanent finger extension.
- Speech input may be a solution for specific situations like straight-forward writing of correspondence, but can’t, at present, fully substitute hand-operated input devices. Some users have developed severely sore throats after intensive speech input.

Software design and software usage

- Software should be designed to minimise the need for mouse-clicks and especially double-clicks.
- Software should be designed to minimise the need for unnecessary or long-lasting manipulation of objects on the screen. Prolonged device operation with depressed fingers (dragging) should be reduced.
- Distances between interactive elements on the screen used in conjunction or sequence (e.g. icons, programme controls or items within dialogue boxes) should be reduced.
- Software should permit alternative methods to undertake selection or manipulation tasks, e.g. keyboard shortcuts.
- If keyboard shortcuts are not provided, create your own. Some shareware tools allow to create not only shortcuts for simple commands in any programme, but also macros for extended sequences of operations. Or look for a software like ‘Mousetool’ that watches your mouse movements. Depending on the context and underlying window, this programme will automatically perform a click or double-click as soon as you stop the pointer over a sensitive area.
- Use both hands to type combination key strokes (like shift-, ctrl-, alt-). The usual combinations to copy, cut and paste text (ctrl-c, ctrl-x, ctrl-v) are often executed using the pinkie and index finger of the left hand, because the right hand is being used on the mouse to select the text or position for the specific operation. This leads to a straining finger abduction and hand pronation.

Workstation

- Common recommendations on desk and chair height, screen positioning etc. offer good guidelines, but variability mighty be the most important principles. Variability means dynamic sitting (chair model, change of posture, chair height, leaning against the back rest or not, etc.), standing up for certain tasks (phone calls, conversations) or during breaks, varying the tasks and many more. Height adjustable desks that can also be used in standing and chairs with good adjusting possibilities support variability.

- L-shaped desks or desks with a half-round cutting offer the possibility to lay down both forearms

Work organisation:

- Employees should be given the option to try and compare different pointing devices. While there is considerable scope to specify other features when making computer purchases (memory, monitor etc) there is often only limited, if any, choice with respect to pointing devices.
- Employees must not be prevented from configuring their device by organisational policy.
- Employees must be educated how to achieve mental and muscular relaxation.
- Employers must ensure that procedures are in place for users to report pain, discomfort, or other problems with devices. Employees must be offered appropriate technical support, medical/ergonomic advice, or organisational change.

Other personal behaviour

- Train body awareness. Feel strain and fatigue before they develop to pain. When you feel strain, ongoing high effort, discomfort or pain, try to relax your neck, shoulders and arms and then try if you can organise your posture, movements and work in a different way that causes less strain. Try to differentiate between necessary and unnecessary activation of all of your muscles. Your body works as an entity – you won't be able to relax your neck as long as you're clenching your toes.
- Avoid monotony. Vary not only posture and mechanical patterns, but change also between work with high and low mental and visual demand. Don't stare into the computer screen all day – switch it off from time to time, for instance during a phone call or a conversation. Your brain and eyes need regular breaks and changes.
- Try to read a document walking. Take the document, a pen and a marker and study it while slowly walking through the park, the corridor or the hall of your office.
- Take frequent, short breaks that permit physical *and* mental relaxation. Include regular micro-breaks of a couple of seconds - stand up, stretch, move. Or keep your seat, close your eyes, relax your limbs, feel your body and think of nothing, and be it for just 10 seconds. Your neck and shoulders can't relax as long as you think of undone jobs.

- Include some simple stretching exercises in your frequent breaks. A simple one for the fingers would be the prayer stretch – hold your hands together, as if you were praying, forearms horizontal, finger tips upwards, pushing your handballs slightly together. Then push the fingers of both hands jointly to one side, hold for 15-30 seconds, and then to the other side. Do this very gently.
- Engage in physical exercise. Choose your sport and make sure it's something that you have fun with and that you can practise several times a week. And be it just a daily walk or taking the bicycle to reach the office. It's not important what kind of workout you choose, as long as you like doing it and are able to practise regularly. It has been shown that movement alone can already reduce pain perception and release people from a vicious circle of pain – muscle tension – more pain.
- Relaxation and body awareness techniques (such as Feldenkrais, Alexander, progressive relaxation, Yoga, Qi Gong and Tai Chi) are useful prevention and therapeutic methods.
- If you already feel pain, seek medical or physiotherapeutic advice. In addition to the above-listed, some other recommended therapeutic therapies include trigger point massage, acupuncture or dry needling. Once chronic pain has established, complete recovery can be long-lasting, and is not always successful.
- The importance of prevention cannot be overemphasised. Change your office setup and behaviour now, and before your are forced to do so by pain. This can save months and years of pain and disability.

Annex: Detailed task description of experiment 3

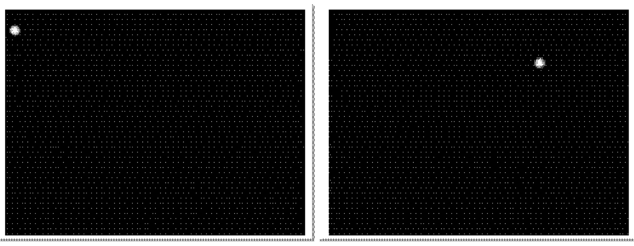
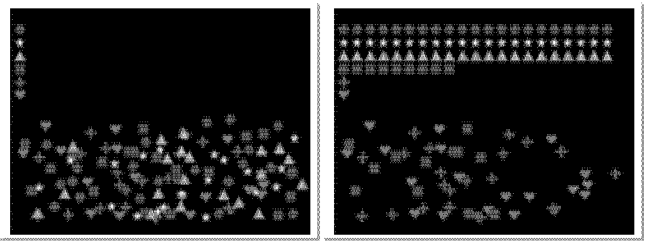
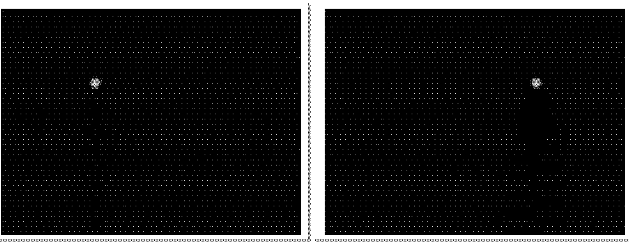
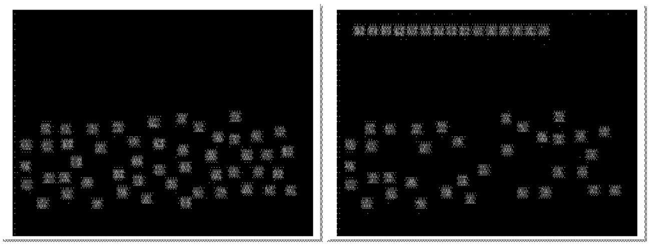
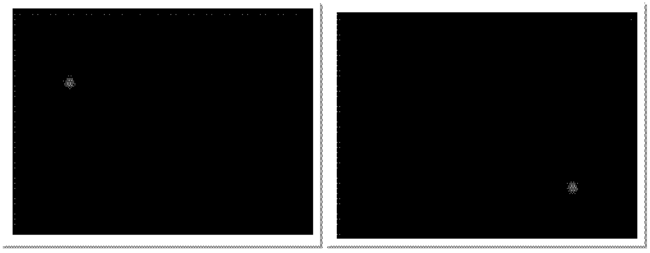
Subtasks A1...A5	
A1: Main subtask, repeated 5 times (motor demand: medium, visual demand: low)	
Clicking on a white dot (ø 10 mm) that will jump to the right by 12 mm after each click. After completion of a line, the dot will jump back to the left border, 20 mm beneath the previous line.	
A2 (motor demand: low, visual demand: low)	
Clicking on 6 kinds of figures scattered over the lower screen half (red dots, yellow stars etc., ø 10 mm approx.) in a given order (first the red dots, then the yellow stars etc., order shown near the left border by one instance of every kind). After clicking, the figures will line up in the upper screen half.	
A3 (motor demand: medium, visual demand: low)	
Clicking on a green dot (ø 10 mm) which will jump between two positions 120 mm apart on a horizontal line.	
A4 (motor demand: low, visual demand: high)	
Sorting 50 numbered squares (10x10 mm) scattered over the lower screen half in ascending order by clicking. The squares will line up in the upper screen half.	
A5 (motor demand: medium, visual demand: low)	
Clicking on a red dot (ø 10 mm) which will jump to a random location after every click.	

Figure 62 B/W screenshots of the subtasks A1...A5 of experiment 3. First screenshot at start, second screenshot (typically) after 50 s.

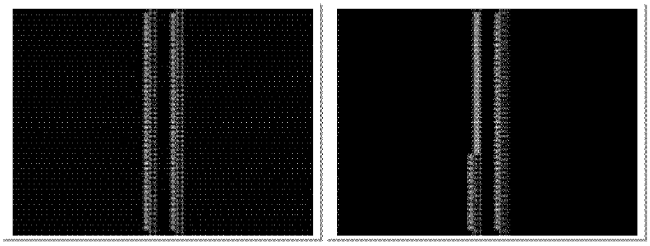
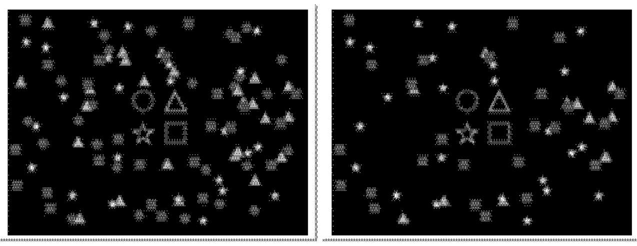
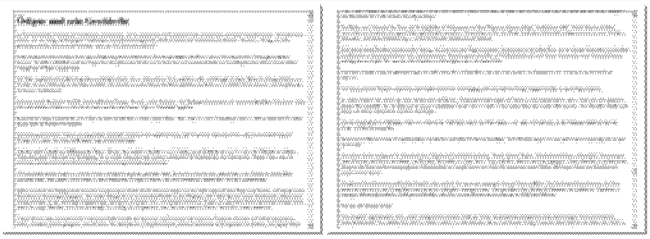
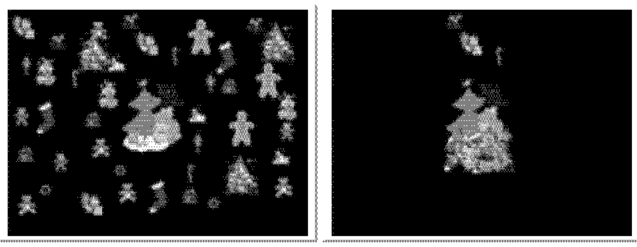
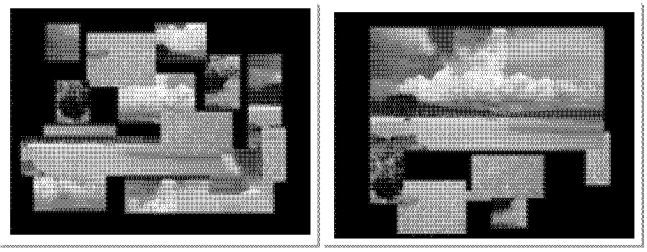
Subtasks B1...B5	
B1: Main subtask, repeated 5 times (motor demand: medium, visual demand: medium)	
Dragging green squares (4x4mm) to the right by 7mm approx., dropping them within a 6x6mm frame, proceeding from top to bottom (left column first). The required precision is that the squares do not overlap the frame borders. No second, corrective moves allowed.	
B2 (motor demand: low, visual demand: low)	
Dragging 4 types of figures scattered over the screen (red dots, green triangles, yellow stars and blue squares, ø 10 mm approx.) in this order (first the red dots, then the green triangles etc.) over the 'correct' figure in the centre and dropping them (red dots in red circle etc.). The figures will then disappear.	
B3 (motor demand: medium, visual demand: high)	
Finding five bold-printed words (hint: names of ancient Greek kings) printed in bold in a 43-page text while navigating only by dragging the right scroll-bar button (no clicking within the text or scroll bar). Say the experimenter the names found.	
B4 (motor demand: low, visual demand: low)	
Dragging, in arbitrary order, different 'Christmas gifts' and dropping them under the Christmas tree.	
B5 (motor demand: high, visual demand: high)	
Solving a puzzle using drag-and-drop. The puzzle pieces will line up to the exact position if dropped within a proximity of 2 pixels of the correct location.	

Figure 63 B/W screenshots of the subtasks B1...B5 of experiment 3. First screenshot at start, second screenshot (typically) after 50 s.

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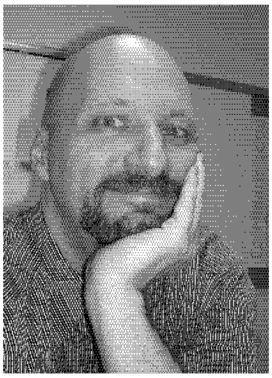
About the Author



Michael Schnoz was born in Disentis/Mustér, Switzerland, in 1964, where he attended elementary school and the Gymnasium, which he completed with the Federal Matriculation Certificate. He studied Electrical Engineering at the Swiss Federal Institute of Technology, Zurich (ETH), focusing on information technology. Two semester theses in neural networks for synthesised speech systems and automated image classification triggered his interest in the neurophysiological field. He graduated with a Master's degree in power electronics in 1995. After some experience in industrial software engineering he returned to ETH in 1997 as a research assistant at the Institute of Hygiene and Applied Physiology. He attended courses in Occupational Health and started his PhD on work related musculoskeletal disorders in 1999 under Professor Helmut Krueger. Since 2003, he has been working at the ETH Web Office where he is, among other things, engaged in web accessibility and the implementation of the law on equal opportunities for handicapped people in the internet. He finished his PhD thesis "On the Role of Trapezius Co-Activity and Unfavourable Motor Unit Patterns in the Development of Muscle Disorders in Human-Computer Interaction" in 2005.