Wrist and thumb joint postures and motions – measurements using electrogoniometry and EMG

Per Jonsson

Institute of Medicine
at Sahlgrenska Academy
University of Gothenburg

2009

UNIVERSITY OF GOTHENBURG

Published and printed by

Intellecta Infolog AB, Göteborg, Sweden, 2009

ISBN 978-91-628-7930-3

Link to e-publicising: http://hdl.handle.net/2077/21193

Wrist and thumb joint postures and motions – measurements using electrogoniometry and EMG

Per Jonsson

Occupational and Environmental Medicine
School of Public Health and Community
Medicine Institute of Medicine, University of Gothenburg

Abstract

Correct measurements of the joints' extreme postures, velocity and repetitiveness are important for studies of the origin of musculoskeletal disorders. Posture measurements of wrist and thumb joints may also provide insights into input device designs that may reduce effort and/or facilitate productivity. Electrogoniometry offers a relatively simple and objective way to measure joint postures and motions. The expectation is that electrogoniometric instruments will provide better measures of postures and movements than the more subjective methods such as self-reporting or observation.

In the first part of this thesis, two wrist goniometer systems were evaluated. The systems differed in how the goniometers were engineered and positioned over wrist and forearm. One system was integrated into a fingerless glove and floated over the forearm whereas the other system was mounted directly over the wrist. ”True” wrist positions were established with the aid of a fixture that allowed the positioning of the wrist in known angles. The “Crosstalk” – when movement in one plane artificially causes movement to be measured in another movement plane, “offset” – where the measured movement axes differ or are offset from the actual movement axes, and “range of motion” – the difference between the actual and measured range of motion of the joint, were compared. The measurement errors were substantial with both systems for simple, standardized wrist postures. However, the system with the transducers built-in in the fingerless glove had considerably less crosstalk errors and proved to have less between-subject differences. The similarities and differences in the measurement errors could be attributed to differences in systems design and methods to improve the accuracy of wrist posture measurement were provided.

In the second part of this thesis, the accuracy and feasibility of measuring thumb postures and movements with a simple thumb-mounted electrogoniometer were evaluated. The ”true” thumb positions were established and defined using a manual goniometer. The posture measurement error of the thumb-based electrogoniometer was small relative to the manual goniometer, and on average, less than 5 degrees. A follow-up study determined whether this simple thumb-mounted goniometer could provide meaningful information on thumb posture during mobile phone use. When measuring thumb posture during SMS messaging, thumb posture was shown to be affected by the size of the mobile phone and differences in movement speeds were seen between the two movement axes of the thumb. Thumb movements in abduction/adduction were almost twice as fast as those in flexion/extension. It was also established that the thumb worked near the extreme ranges of motion – which is known to contribute to musculoskeletal disorders.

Finally, this thesis determined whether measurements with a simple, thumb mounted electrogoniometer could be used in place of more complicated measures of muscle activity (EMG) for assessing musculoskeletal load during mobile phone use. Sophisticated correlation analyses of these different methods showed that only during very limited conditions could thumb goniometry be used in lieu of EMG measurements to assess musculoskeletal loads. Measurements indicated that the thumb's muscle activity most often complemented rather than replaced the simple goniometric measures of the thumb.

Key words: Accuracy, Electrogoniometry, Input device, Information and communication technology, Mobile phone, Muscle activity, Posture, Thumb, Wrist

List of abbreviations

Ad/Ab	Adduction/Abduction
APB	Abductor Pollicis Brevis (muscle)
APL	Abductor Pollicis Longus (muscle)
ARV	Averaged Rectified Values
CMC	CarpoMetaCarpal (joint)
ED	Extensor Digitorum communis (muscle)
EMG	ElectroMyoGraphy
F/E	Flexion/Extension
FDI	First Dorsal Interosseus (muscle)
ICT	Information and Communication Technology
IP	InterPhalangeal (joint)
MCP	MetaCarpoPhalangeal (joint)
MPF	Mean Power Frequency
MVE	Maximal Voluntary Electrical muscular activity
N	Neutral position
n	number of subjects
P/S	Pronation/Supination
R(d)	Normalized cross-correlation function
R/U	Radial/Ulnar deviation
Rmax	Maximal cross correlation value
ROM	Range Of Motion
SD	Standard Deviation
SMS	Short Message Service
TMC	TrapezioMetaCarpal (joint), also named “first carpometacarpal” CMC 1 (joint)
WMSD	Work related MusculoSkeletal Disorders

List of papers

This thesis is based on the following four publications, which will be referred to by their Roman numerals.

I Per Jonsson, Peter W. Johnson. Comparison of measurement accuracy between two types of wrist goniometer systems. *Applied Ergonomics*. 2001 Dec; 32(6):599-607.

II Peter W. Johnson, Per Jonsson and Mats Hagberg. Comparison of measurement accuracy between two wrist goniometer systems during pronation and supination. *Journal of Electromyography and Kinesiology*. 2002 Oct; 12/5: 413-420.

III Per Jonsson, Peter W. Johnson and Mats Hagberg. Accuracy and feasibility of using an electrogoniometer for measuring simple thumb movements.
Ergonomics. 2007 50(5): 647-59.

IV Per Jonsson, Peter W. Johnson, Mats Hagberg and Mikael Forsman. Thumb joint movement and muscular activity during mobile phone texting – a methodological study. *Submitted for publication*.

Contents

1 INTRODUCTION

1.1 The hand

The function of the hand is central in all human activity and has played a crucial role in the evolution of mankind. Apart from being a tremendously flexible griping tool, the hand has important functions in communications, body language and touch. Despite all the recent mechanization of production activities in industry, proper functioning of the hand is a necessity in both private and working life (Hägg, 2001).

Especially the thumb is important for proper hand function and its role is central in the performance of simple everyday tasks such as grasping and pinching. Thumb operated calculators, remote controls, game controls and mobile phones have become an integral part of modern life.

1.2 Musculoskeletal disorders and exposure

The position, frequency, velocity, acceleration and daily duration of hand movements are thought to be important factors which may play a role in the development of upper extremity work related musculoskeletal disorders (WMSDs). Placing the wrist in flexion causes tendons to press against the median nerve and will increase the pressure in the carpal tunnel. Repetitive , and even passive, flexion/extension will "pump up" this pressure (Hagberg et al., 1995). For workers in industrial tasks, velocity and acceleration parameters have been associated to cumulative trauma disorders (CTDs) which demonstrate the importance of dynamic components of wrist measurements (Marras and Schoenmarklin, 1993). Hand, thumb and finger intensive work with repeated, static or extreme finger postures may lead to pain and discomfort, decreased performance and sick leave. Increased risk for thumb joint osteoarthritis has been reported for a large number of occupations involving repetitive thumb use (Fontana et al., 2007). A case with pain and arthritis at the base of the thumb after excessive mobile phone texting has been reported (Ming et al., 2006). De Quervain's tenosynovitis is characterized by pain on the thumb side of the wrist because of thickening of the ligamentous structure covering the tendons and may follow thumb overexertion (Moore, 1997). Musculoskeletal symptoms related to thumb intensive work with automatic pipettes in laboratory work has been reported. (Fredriksson, 1995). Some of the thumb-related disorders have been given names such as 'Nintendonitis' and 'Blackberry Thumb' to attribute the disorder to the device that was believed to aggravate the joint. In the past decade, there has been a rapid increase in the use of mobile phones and other small hand-held devices for pleasure and communication (e.g. iPods, web-based smart phones, etc.), text messaging and games. In Sweden, the number of text messages increased 70 % from 2.9 billion in the year of 2006 to 4.8 billion in 2007 (National Post and Telecom Agency, 12 June 2008 http://svensktelemarknad.se/PTS2007/index.html). The uses of these hand-held devices will probably continue to increase, especially among adolescents. The extended intensive use of mobile phones and other devices for Information and Communication Technology (ICT) could expose the thumbs and fingers to operational stresses beyond their intended function which may generate pain and musculoskeletal disorders in the thumbs and the associated joints. Objective physical measurements associated with the use of hand-held devices can provide a foundation for recommendations on how to reduce the physical loads and perhaps how to increase efficiency of use during operation. Accurate, objective measures of hand exposure are therefore important to reduce the occurrence of WMSDs.

1.3 Exposure measurements

1.3.1 PAST STUDIES TO CHARACTERIZE JOINT MOVEMENTS

Several methods exist to measure and characterize joint movements. The systems vary in complexity and accuracy and no ideal system exists. The data quality is comparable with a conventional manual 1-D goniometer, which is accurate to ±5° and sufficient for clinical purposes. To obtain thumb postures, (Kinoshita et al., 1996) made simple marks with a felt pen on a cylinder and compared these with a protractor. Video-based methods use either active or passive optical markers attached to the surface of the skin and provide a non-invasive approach for obtaining 3-D quantitative measurements of in vivo joint kinematics, (Tang et al., 2008), (Kuo et al., 2002), (Chiu et al., 1998). The use of electromagnetic systems is another way to measure and characterize joint movements (Kuo et al., 2003). These systems use electromagnetic markers whose locations can be identified in a 3-D space using electromagnetic sensors. The video-based systems are limited if the optical markers are obscured from the view of the cameras and the electromagnetic devices can interact with any metallic or electric devices in the environment, resulting in measurement error. In addition, both systems require the use of advanced computational calculations to obtain the wanted thumb kinematics. In both occupational and clinical research settings, there is need for simpler and more cost-effective, but nevertheless accurate, methods to characterize simple joint postures and movements. Electrogoniometry is one such method that is relatively inexpensive and accurate for measuring joint angles and has been used on the wrist, but not previously on the thumb.

1.3.2 ELECTROGONIOMETERS

With the introduction of electrogoniometers, the measurement of joint postures and movements can be continuously captured where after the data can be used to characterize posture, repetitiveness and velocity of joint movements. (Hägg et al., 1997), (Hansson and Mikkelsen, 1997) , (Hansson et al., 1996), (Radwin and Lin, 1993). This implies a great improvement in time resolution compared to manual goniometry. Accuracy of the measurements is essential in joint studies. Moreover, when deriving velocity and acceleration, certain errors in position data will propagate and may even be amplified by the derivate process. (Van Vorhis, 1996). Previous studies on human hands have shown that wrist electrogoniometry is prone to measurement errors depending on the degree of flexion/extension, radial/ulnar deviation and forearm rotation (Hansson et al., 2004), (Buchholz and Wellman, 1997). In the thesis the accuracy of various electrogoniometric systems will measured and evaluated. The first half of the thesis will compare the accuracy of two electrogoniometer systems for wrist angle measurements. The accuracy will be related to the “true” measure captured with manual goniometry.

Although electrogoniometer systems have been developed and extensively validated for measuring wrist posture, data is limited on the suitability of using electrogoniometers to measure thumb posture and movements. In the second half of the thesis, the accuracy, related to manual goniometry, will be tested for a commonly used electrogoniometer attached on the thumb. Furthermore, the feasibility of thumb electrogoniometry will be tested.

1.3.3 ELECTROMYOGRAPHY

Besides registering thumb movements with electrogoniometry, characterizing thumb-related muscle activity is also of importance. Muscular activity can be captured with electromyography (EMG) and is used to characterize muscular load and rest (Hansson et al., 2008), (Mork and Westgaard, 2007), (Merletti et al., 2004), (Hansson et al., 2003) (Westgaard et al., 2001), (Basmajian and De Luca, 1985). While issues related to wrist electrogoniometry and forearm EMG have received substantial attention (Hansson et al., 2008), the combined use of these tools for characterizing thumb-based activities has not been widely investigated. There is an obvious relationship between thumb's movements and the muscle activity in the arm and hand; in the thesis the association between thumb-goniometry and muscle activity will be elucidated.

2 AIM

The aim of this thesis was to study electrogoniometry and EMG for measuring wrist and thumb postures and movements typically encountered when using hand-held device during ICT work.

Specific aims:

2.1 Wrist posture measurement accuracy

Study I & II: To compare the accuracy of a commonly used biaxial, single transducer electrogoniometer system and a biaxial, two-transducer electrogoniometer system for measuring wrist postures with the wrist placed in known positions using a positioning apparatus considered to be the gold standard.

2.2 Thumb posture measurement accuracy

Study III: To determine the accuracy of a commonly used biaxial, single transducer electrogoniometer for measuring thumb postures with the thumb placed in known positions using a positioning apparatus considered to be the gold standard.

2.3 Feasibility of thumb electrogoniometry

Study III: To determine the feasibility of a commonly used biaxial electrogoniometer for measuring thumb postures and movements during mobile phone text messaging.

2.4 Thumb electrogoniometry and EMG associations

Study IV: To determine whether there are any associations between thumb-based exposures registered with a relatively easy-to-use electrogoniometric method and the more involved and complicated EMG method. Specifically, at the group level, (using group summary measures) the purpose is to determine whether there are any substantial and physiologically meaningful correlations between thumb-based electrogoniometry and EMG parameters. Moreover, to determine the correlations at the individual signal-to-signal level by temporally comparing each individual's synchronously sampled goniometry and EMG signals. If either group or individual level correlations exist between the two methods, then under certain circumstances, the simpler electrogoniometric methods may be used as surrogate measures for the more complicated EMG measures.

3 METHODS

3.1 Subjects

3.1.1 WRIST JOINT – STUDY I & II

Three men and five women volunteered to participate in the study. These subjects were recruited from the Department of Occupational and Environmental Medicine at the Sahlgrenska University Hospital, Gothenburg, Sweden, and they participated in the experimental sessions during work time. The mean age was 31 (range 19 to 54) years.

3.1.2 THUMB JOINT – STUDY III & IV

Fifteen healthy subjects, who reported to be free of pain in the hands, wrists, arm and shoulders during the last 12 months, were selected from a list of text message (short message service, SMS) users and/or mobile phone gamers. The subjects were a subset of a Swedish cohort of young ICT users (Thomée et al., 2007). Seven subjects were women and eight were men, the mean age was 22 (range 20 to 25) years. All subjects gave their informed consent and all experimental procedures have been approved by the human ethics committee at the University of Gothenburg.

3.2 Equipment

3.2.1 WRIST ANGLE MEASSUREMENT – STUDY I & II

Two wrist electrogoniometer systems were evaluated (Figure 1). The first system, designated as System A, was a commonly used system consisting of a single-transducer, biaxial goniometer (Model X 65; Biometrics; Cwmfelinfach, Gwent, UK) connected to an 8-bit portable data logger sampling at 20 Hz (Model DL 1001; Biometrics; Gwent, UK). The transducer measures movements in two planes, Flexion/Extension and Radial/Ulnar. Negative angles were used to denote flexion and radial deviation.

The second, System B, which is no longer commercially available, consisted of a two-transducer, biaxial goniometer connected to a 12-bit portable data logger (WristSystem; Greenleaf Medical; Palo Alto, California) sampling at 20 Hz.. Each of the two transducers measures Flexion/Extension (F/E) and Radial/Ulnar (R/U) movements respectively. The redundant information from the biaxial goniometers is used for error correcting algorithms, which are described in system B's patent (Edwards et al., 1996).

Both systems' transducers were applied on the dorsum of the hand and on the distal forearm.

Goniometer System A was attached to the subjects' right wrist using the methods prescribed by (Buchholz and Wellman, 1997). A straight line was drawn from the third metacarpophalangeal joint along the third metacarpal segment through the wrist joint and out to the lateral epicondyle. The distal endblock of the electrogoniometer was centred over the line drawn on the hand and attached using double-sided tape. The participant's wrist was extended, and the proximal endblock of the electrogoniometer was then centred on the line drawn on the forearm and attached as close to the wrist as possible without distorting the electrogoniometer wire using double-sided tape. Adhesive tape was placed over each endblock to minimize movement of the endblocks from this setup orientation. Since both endblocks were rigidly secured to the hand and forearm, any rotation between the two endblocks, which may occur during wrist movements, may twist the sensing beam and potentially result in crosstalk measurement errors (Hansson et al., 1996); (Buchholz and Wellman, 1997).

System B was secured to the subject's wrist using a lycra fingerless glove delivered with the system. The glove was attached by sliding the integrated glove and transducer system over the subject's hand and securing three velcro straps on the glove. To ensure that the glove was securely attached to the hand but loose enough around the forearm to allow the glove to slide over the skin, the experimenter put one finger under the glove and tightened the straps over his finger. The distal endblock of System B was secured to the back of the hand, but the proximal endblock on the forearm contained a circular channel. The channel allowed the terminal portion of the transducer, which was a circular cylinder of slightly smaller diameter, to freely slide and rotate within the proximal endblock. Thus, any rotation between the two endblocks which may occur during forearm pronation/supination should not be transmitted sensing device of the electrogoniometer, and thereby reduce measurement errors.

In addition, unlike System A, System B's fingerless glove system allowed the proximal endblock to freely slide over the skin of the forearm, this reduced the movement artefacts associated with skin and/or bone movement under the endblocks that occur during pronation/supination.

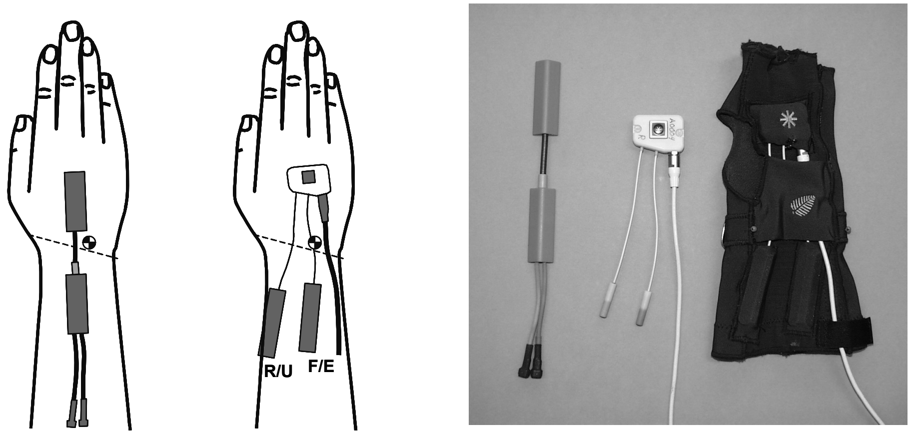


Figure 1. Left half of figure illustrates how the wrist goniometers were mounted on the wrist, System A (left) and System B (right). Right half of figure shows a photo of the systems, System A (left); System B (middle); System B inside the fingerless glove (right). To facilitate comparisons of how the systems reside on the wrist, System B in the left half of the figure is shown without the fingerless glove. The dashed line and the circle represent the anatomical flexion/extension axis and radial/ulnar deviation centres of movement respectively (Youm and Yoon, 1979); (Van Vorhis, 1996); (Moore et al., 1993).

3.2.1.1 The wrist positioning apparatus

A calibration fixture delivered with System B (Figure 2) was securely attached to a tiltable, adjustable-height table (Figure 3) and was used to repeatedly position each subject's wrist in known R/U, F/E and P/S angles. The calibration fixture allowed wrist movement in one plane (F/E) while the subjects were asked to restrict motion in the other plane.

Using a manual goniometer, the R/U angles were defined by placing the subject's hand in the calibration fixture in the neutral F/E position, and moving the hand into –10, 0, 10 and 20 degrees of R/U deviation (negative values indicate radial deviation). In each R/U position an outline of the hand was traced on the base of the calibration fixture (Figure 2), this ensured the repeatable repositioning of the subject's hand in these R/U positions throughout the experiment. These R/U positions outlines were created in the neutral F/E position (0 F/E) and it was assumed that these R/U positions would be virtually the same in the other F/E positions.

The F/E angles were defined by placing the subject’s hand in the calibration fixture in the neutral R/U position. The calibration fixture had an analogue scale for measuring F/E positions (Figure 2). Using a manual goniometer, the hand was positioned in - 40°, - 20°, 0°, 20°, and 40° of F/E and the analogue scale settings on the calibration fixture were noted down to ensure the repeatable repositioning of the various F/E positions throughout the experiment. These F/E positions were identified in the neutral R/U position (0 R/U) and it was assumed that these F/E positions would be virtually the same in other R/U positions.

The P/S angels were maintained by placing the forearm in the calibration fixture on the tiltable table. The various P/S positions were verified by tilting the table and making use of a inclinometer/water level (Figure 3, bottom row and Figure 4.) Four different pronation and supination positions were tested: palm down, 90° pronation (90 P); 45° pronation (45 P); palm vertical, 0° neutral (0 N) and 45° supination (45 S).

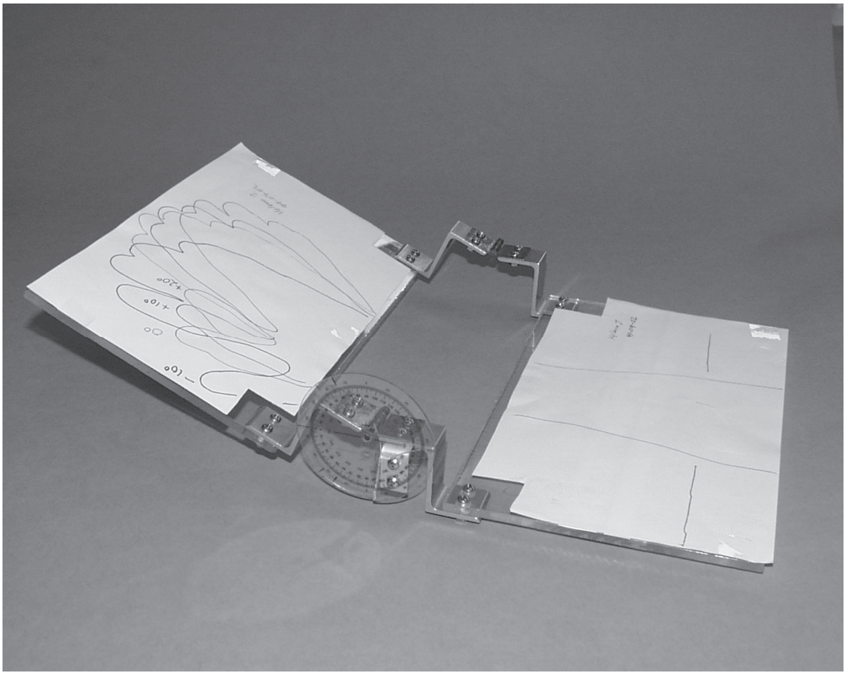


Figure 2. The calibration fixture, note the analogue scale for F/E movements and the outlines for R/U movements.

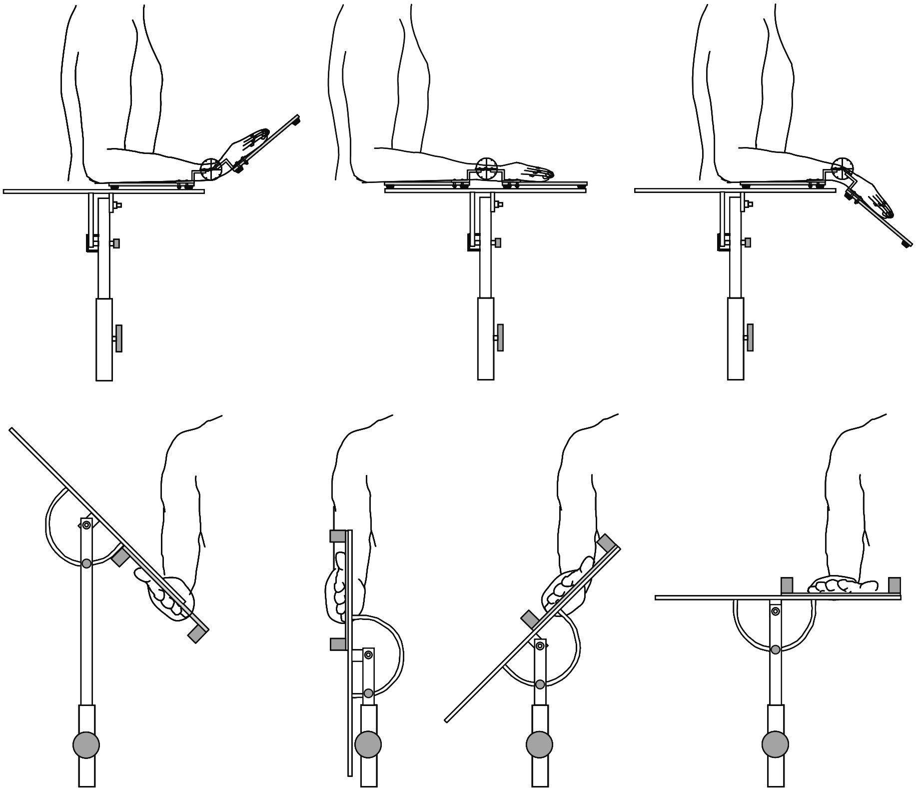


Figure 3. The calibration fixture attached to the tiltable table demonstrating how the wrist positioning apparatus was used. Top row shows how the apparatus was used to position in extension and flexion. Bottom row from left to right shows how the apparatus was used to position the wrist and forearm in 45° supination, 0° neutral, 45° pronation and 90° pronation respectively.

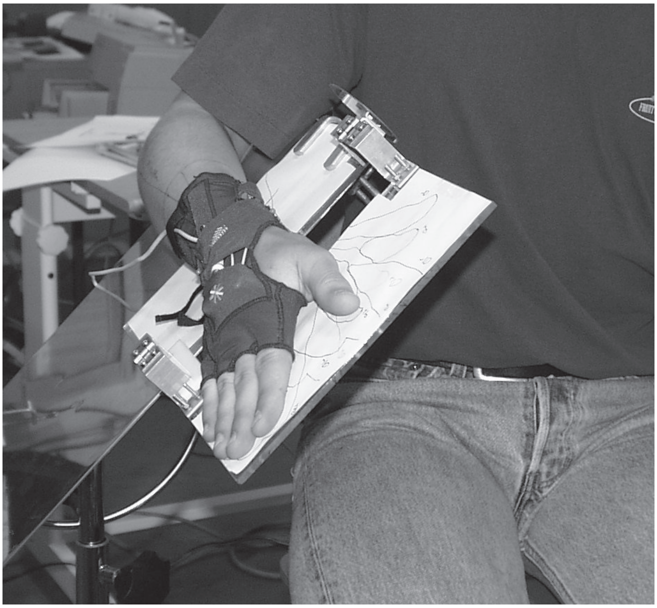


Figure 4. The calibration fixture attached to the tiltable table demonstrating how the wrist positioning apparatus was used. The posture here is 45° pronation, neutral F/E and 20° ulnar deviation with system B.

3.2.1.2 Calibration

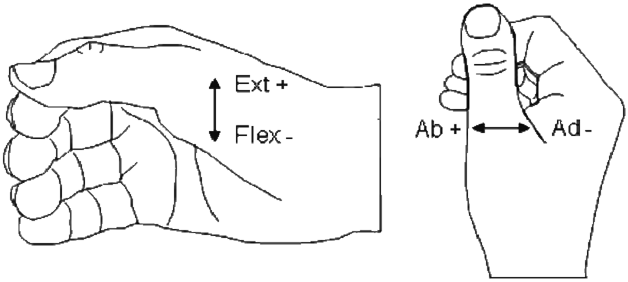
The goniometers were calibrated with the subject's wrist in 90˚ pronation in the calibration fixture. Neutral wrist postures were defined and measured using the clinically accepted standards prescribed by the American Academy of Orthopaedic Surgeons (Greene et al., 1994). The neutral position was defined when the plane of the back of the hand was in line with the plane on the dorsal surface of the forearm and when the third metacarpal bone was perpendicular to the axis of F/E. System A was calibrated by placing the subject's wrist in a neutral F/E and R/U position and offsetting/recording the zero positions by pushing a button on the goniometer's logger. Using a manual goniometer, System B was calibrated by putting the wrist in five different calibration positions (Table 1) and storing each position in the logger's memory. As a result of these calibration procedures, System A had a universal gain, which was the same for all subjects but System B had gains specific to each subject and used a crosstalk error correcting algorithm (Edwards et al., 1996).

Table 1. Calibration positions in degrees for System B, flexion and radial deviation are indicated by negative angles.

Position	Flexion/Extension	Radial/Ulnar Deviation
1	0	0
2	40 (extension)	0
3	-40 (flexion)	0
4	0	-10 (radial)
5	0	20 (ulnar)

3.2.2 THUMB ANGLE MEASUREMENT– STUDY III & IV

Thumb adduction/abduction (ad/ab) and flexion/extension (flex/ext) was measured using an electrogoniometer system, adduction and flexion angles were given negative values as defined in figure 5. The system consisted of a biaxial goniometer (Model SG 110; Biometrics; Gwent, UK) connected to a 12-bit portable data logger (Muscle Tester ME3000P8, Mega Electronics Ltd., Kuopio, Finland) with the data collected at 1000 Hz. The raw data from the electrogoniometer as well as EMG electrodes (described later) were monitored in real-time on a laptop computer for quality control and recorded on-line to the computer's hard disc. Figure 6 shows how the electrogoniometer resided on the thumb. Using double-sided tape, the goniometer endblocks were attached to the subjects' right thumb and wrist with the distal endblock over the proximal phalanx and the proximal endblock over the radius bone. Thus the goniometer measured the combined angle of the first metacarpophalangeal (MCP) joint, the trapeziometacarpal joint (TMC, also named the first carpometacarpal, CMC 1) and the scaphoradial joint (Figure 6b, 7a).



(a) (b)

Figure 5. Definition of the neutral flexion/extension (flex/ext) posture (a), neutral adduction/abduction (ad/ab) posture (b) and sign conventions used to define thumb positions.

(a) (b)

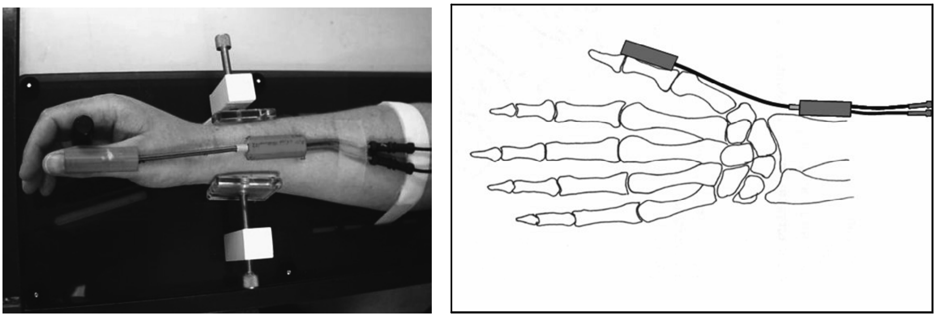


Figure 6.
(a) Top view of the hand in the goniometer calibration fixture with the electrogoniometer mounted to the thumb and forearm. The thumb is in neutral adduction/abduction position;
(b) illustration of electrogoniometer mounting demonstrating how the electrogoniometer spanned the metacarpophalangeal joint, the trapeziometacarpal joint and the scaphoradial joint.

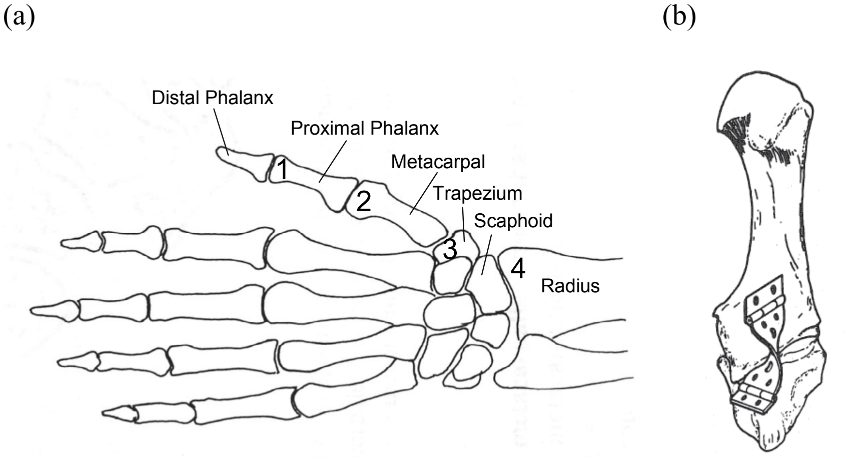


Figure 7. Bones and joints of the thumb.
(a) 1 = interphalangeal (IP) joint responsible for thumb flexion/extension about the IP joint; 2 = metacarpophalangeal (MCP) joint responsible for thumb flexion/extension and abduction/adduction about the MCP joint; 3 = trapeziometacarpal (TMC) joint responsible for thumb flexion/extension, abduction/adduction and circumduction about the TMC joint, also named the first carpometacarpal (CMC) joint; 4 = scaphoradial joint responsible for thumb flexion/extension and wrist radial/ulnar deviation.

(b) Model of the TMC joint adapted from (Hollister et al., 1992). The TMC joint has two axes of motion symbolically represented by two offset hinges in the figure. The first axis in the base of the figure is in the trapezium and represents the flexion/extension axis. The second axis attached to the base of the metacarpal bone represents the abduction/adduction axis. As illustrated by the twist in the hinge, the second axis is attached to the first axis and the two axes do not lie in the same anatomic plane.

3.2.2.1 The thumb positioning apparatus

To repeatedly position each subject's thumb in known Ad/Ab and Flex/Ext angles, the subject's right hand and forearm were placed in a custom-made calibration fixture (as shown in figure 6a). The fixture allowed thumb movements while simultaneously restricting unwanted wrist movements.

3.2.2.2 Calibration

As shown in figure 6a, the electrogoniometer was calibrated with the subject's wrist fixed in the goniometer calibration fixture in a neutral pronation/supination position (the neutral posture being defined in figure 5). The neutral (0˚) Flex/Ext thumb posture was defined as where the line through the IP joint and MCP joint was parallel with the top of the long axis of the index finger. The neutral (0˚) Ad/Ab thumb posture was defined as the position where the IP joint, MCP joint and TMC joint were in line with the long axis (radius bone) of the forearm. These two zero positions were marked in the electrogoniometer data using an event marker, which was triggered by pushing a button on the logger. Using the manual goniometer, the thumb was then put in two calibration positions, 20˚ abduction and 40˚ extension and these two positions were also marked in the electrogoniometer data. The differences between the respective zero positions and calibration positions were used by the logger to derive the gain for each goniometer channel. Hence, specific zeros and gains were derived by the logger for each subject.

3.2.3 ELECTROMYOGRAPHY – STUDY IV

Bipolar surface electromyography (EMG) was registered in four muscles on the right forearm and thumb: the extensor digitorum communis (ED), abductor pollicis longus (APL), first dorsal interosseus (FDI) and the abductor pollicis brevis (APB). These muscles were chosen for their relevance to hand and wrist function during mobile phone grasping but also for the possibility to position surface electrodes over part or all of the muscle belly with minimal interposition of more superficial muscles. Disposable 10 mm diameter surface EMG electrodes (Blue Sensor N, Ambu A/S, Ballerup, Denmark) were used with 20 mm center-to-center inter-electrode spacing. Prior to electrode attachment, the skin was dry shaved, cleaned with alcohol, abraded with sandpaper and cleaned with a gauze pad saturated with water.

The EMG electrodes over the muscles were placed as recommended by (Perotto and Delagi, 1994) (Figure 8). The ground electrodes were placed over extensor aponeurosis and ulna in the forearm.

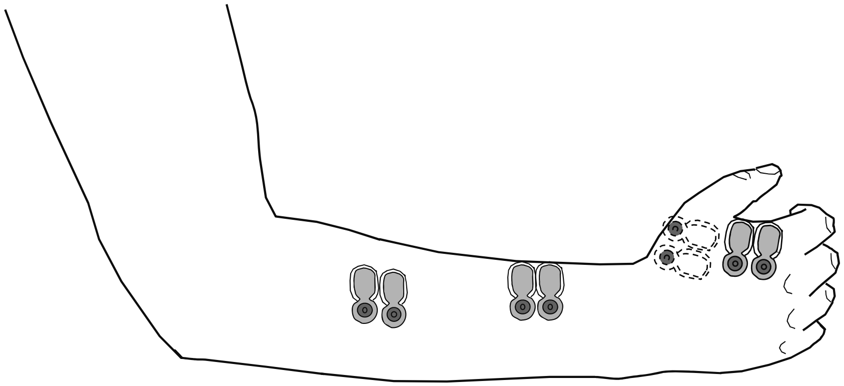


Figure 8. Placement of the bipolar surface EMG electrodes (gray) over the muscles of the ED, APL, FDI (from left) and APB (dashed, hidden).

Along with the electrogoniometry data, the EMG signals were pre-amplified and recorded with a portable EMG system (Muscle Tester ME3000P8, Mega Electronics Ltd., Kuopio, Finland). The EMG signals were filtered with two analogue Butterworth filters; a 3rd order high-pass filter at 8 Hz and a 4th order low-pass filter at 500 Hz, and sampled at 1000 Hz by a 12-bit analogue-to-digital converter. The raw data from the EMG electrodes as well as electrogoniometer (described earlier) were monitored in real-time on a laptop computer for quality control and recorded on-line to the hard disc.

3.2.3.1 Normalization

For normalization purposes, maximal voluntary electrical activities (MVEs) were obtained by having subjects to perform three, five second maximum static contraction against manual resistance (Mathiassen, 1995). The subjects performed the contractions while seated, with their forearm supported on table surface adjusted to elbow height. For ED, the hand and forearm was fully pronated (90º) for the other muscles the forearm was in a neutral position with 0º of pronation.

3.3 Experimental procedures

3.3.1 WRIST POSTURE MEASUREMENT ACCURACY – STUDY I & II

The previously described wrist positioning apparatus was used to position the forearm and wrist in different P/S and wrist angle combinations. The apparatus was adjusted so the subject's arm was resting comfortably at their side, forming a 90° angle at the elbow. Throughout the study, the same person instructed the subjects to hold their wrist in the required position. The wrist was positioned in each R/U position and moved through F/E. Each wrist posture was held for five seconds and data from the goniometers were stored in the memory of the loggers.

The wrist angles used to position the wrist in the apparatus were considered to be the "Gold Standard" and the wrist angles measured by the goniometers the dependent variable.

3.3.1.1 Measurement positions – Study I

With the subject's hand in 90° of pronation, the wrist was moved from 40° of extension to 40° of flexion in 20° increments while in 20°, 10°, 0° of ulnar deviation and 10° of radial deviation. Thus, a total of 20 different F/E and R/U wrist positions were measured spanning a wide range of wrist movements. The aggregate of these 20 positions represented a movement matrix. The order in which the goniometer systems were used was randomised across the subjects.

3.3.1.2 Measurement positions – Study II

The subject's hand where tested in four different pronation and supination positions: 90 P, 45 P, 0 N and 45 S. In each P/S position, subjects moved from 40° of extension to 40° of flexion in 20° increments while in 0° of R/U deviation and from 20° of ulnar deviation to 10° of radial deviation in 10° increments while in 0° of F/E. The aggregate of these 8 different positions will be referred to as identity movements. With the four P/S positions, a total of 32 different wrist positions were measured. The order in which the goniometer systems were tested was randomised across the subjects. With each goniometer, the P/S positions were also randomised.

3.3.2 THUMB POSTURE MEASUREMENT ACCURACY – STUDY III

To repeatedly position each subject's thumb in known Ad/Ab and Flex/Ext angles, the subject's right hand and forearm were placed in the previously described thumb positioning apparatus shown in figure 6a). The subject sat in an adjustable height chair at an adjustable height table. The subject's chair was adjusted so his/her feet rested flat on the floor and the height of the table was adjusted to be at elbow level when the subject's arm was resting comfortably at their side, forming a 90° angle at the elbow. This permitted the subject's forearm to be supported in a neutral pronation/supination posture within the calibration fixture (Figure 6a). Each position was held for five seconds and the data from the goniometers were stored on a hard disk.

The manually measured thumb angles used to position the thumb in the goniometer calibration fixture were considered the 'Gold Standard' and the thumb angles measured by the electrogoniometers were the dependent variables.

3.3.2.1 Measurement positions

Using the manual goniometer, the thumb was positioned in eight different Flex/Ext and Ad/Ab angles: 1) neutral Ad/Ab; 2) 20° abduction; 3) maximal voluntary abduction; 4) maximal voluntary flexion; 5) 20° flexion; 6) neutral Flex/Ext; 7) 40° extension; 8) maximal voluntary extension. For the maximal positions, the values from the manual goniometers were noted for subsequent comparison to the values recorded by the electrogoniometers.

3.3.3 FEASIBILITY OF THUMB ELECTROGONIOMETRY – STUDY III

In order to determine the feasibility of the electrogoniometer for measuring thumb-based movements, an experiment was conducted using a subset of ten subjects. In a laboratory setting, the subjects were asked to sit and enter a 300 character SMS message of their own using a mobile phone. They were instructed to sit in the same position and use the work and texting techniques that they used in real life. Subjects were asked to perform this task twice; once they typed the SMS message using their own mobile phone and once they typed the same message using a standard mobile phone (Model 3310; Nokia, Espoo, Finland). The order of the two phones was randomized and subjects were instructed to type the same message on each phone. The sizes of the mobile phones were slightly different and presented in table 2. The purpose of the task was to characterize thumb postures and movements during a common mobile phone activity and determine if there were any differences in thumb postures and movements between phones. Postures were characterized by extreme adduction/ flexion posture, median posture and extreme abduction/extension. Movements were characterized by angle velocity (˚/s) and mean power frequency (MPF; Hz), which are commonly used measures of repetitiveness (Hansson et al. 1996). The typical duration for the SMS task was 202 s. Figure 9 shows the experimental setting.

Table 2. Size of the standard mobile phone and the mean size and (range) of the subjects' own phones.

Size in millimetres (mm)	Length	Width	Thickness
Standard phone:	113	48	22
Own phone:	107	47	20
	(97 to 124)	(43 to 51)	(17 to 23)

Figure 9. Subject entering a text message on a mobile phone. The picture shows the goniometer spanning the wrist joint and mounted on thumb, the EMG electrodes mounted on the hand and forearm, and the logger used to record and pass the data onto the PC.

3.3.4 THUMB ELECTROGONIOMETRY AND EMG ASSOCIATIONS – STUDY IV

In order to determine the associations between thumb-based exposures registered with electrogoniometry and EMG the same experimental setting was used as in 3.3.3 Feasibility of thumb electrogoniometry – Study III: Fifteen subjects were instructed to enter a 300-character text message of their own choosing using the standard mobile phone (Model 3310; Nokia, Espoo, Finland). The mean duration for the texting task was 222 s. Goniometer and EMG summary measures were calculated from continuously sampled data from each task.

3.4 Data analysis

After the experiments, the data were transferred to the hard disk of a computer for subsequent analysis.

3.4.1 WRIST AND THUMB GONIOMETRY ACCURACY – STUDY I, II & III

Joint postures and movements were calculated for each subject using an interactive data analysis program written in Labview™ (National Instruments Corporation; Austin, Texas, USA). The goniometer data were displayed in a graph, and by using two interactive cursors, a time window of goniometer data could be selected for analysis. For each wrist and thumb position, angles were calculated by taking a 1 s mean [average] of 20 data points in the middle for each 5 s position record.

3.4.1.1 Wrist goniometry accuracy – study I & II

With the summary data from the 8 subjects, the group mean and range of the angles were calculated. For each wrist position, the measurement errors for the electrogoniometer were calculated as the difference between the position in which the wrist was placed by using the wrist positioning apparatus (Gold Standard) and the angle registered by the electrogoniometer. Finally, over the 80° of movement in F/E and the 30° of movement in R/U deviation, the range of movement (ROM) and crosstalk values were calculated for each subject.

3.4.1.2 Thumb goniometry accuracy – study III

First, by taking every 50th sample, the thumb postural data collected at 1000 Hz was resampled at 20 Hz. With the summary data from the 15 subjects, the group mean, standard deviation and range of the angles were calculated. For each thumb position, the measurement errors for the electrogoniometer were calculated as the difference between the position in which the thumb was placed by using manual goniometry (Gold Standard) and the angle registered by the electrogoniometer. Both mean group difference and the mean of the absolute individual differences were calculated for the various Flex/Ext and Ad/Ab positions.

3.4.2 FEASIBILITY OF THUMB ELECTROGONIOMETRY – STUDY III

The thumb postural data was resampled at 20 Hz. This sampling rate has been used before and was found to be sufficient for characterising of wrist movements in highly repetitive tasks (Hansson et al., 1996). An amplitude probability distribution function was calculated from goniometry data collected for each subject during the SMS tasks performed in the laboratory and the 5th percentile angle represented extreme adduction and flexion posture, 50th percentile median posture and the 95th percentile extreme abduction and extension. With the summary data from the subset of 10 subjects using the two mobile phones, the group means and standard deviations of the percentiles, velocities and MPFs were calculated..

3.4.3 THUMB ELECTROGONIOMETRY AND EMG ASSOCIATIONS – STUDY IV

The experiment was conducted on 15 subjects during the standardized SMS tasks performed in the laboratory.

3.4.3.1 Thumb goniometry

The thumb postural data was resampled from 1000 Hz down to 20 Hz. Totally 12 goniometric parameters were calculated for each axis of movement; these are listed and described in Table 3.

Three percentiles were calculated for each movement plane: the 10th percentiles were used to characterize the individual's peak adduction and peak flexion postures, the 50th percentiles (median posture), and the 90th percentiles to characterize peak abduction and peak extension postures (Kazmierczak et al., 2005, Hansson et al., 2008).

Movements were characterized using absolute angle velocities (°/s) and10th, 50th and 90th percentiles were used to describe the individual's low, median and peak velocities respectively.

Two velocity limits, below 5 °/s and 10 °/s, were evaluated for the definition of movement pauses. For these pauses, the percentage of time, mean duration and number of pauses per minute were calculated.

Table 3. The goniometric parameters listed and explained

Goniometry parameters for flexion/ extension and adduction/abduction	Explanation
10th percentile velocity	Low absolute velocity; velocities, in any direction, were below this value only 10% of the time.
50th percentile velocity	Median absolute velocity; half of measuring time velocity is under this value and half time above.
90th percentile velocity	Peak absolute velocity; velocities were above this value only 10% of the time.
Relative pause time	Percentage of measured time when absolute angle velocities were below 5 or 10 °/s *.
Pause frequency	Pauses per minute; number of periods of absolute velocity below 5 or 10 °/s * per minute.
Pause Duration	Mean duration of pauses with absolute velocity below 5 or 10 °/s *.
10th percentile posture	Peak posture in the adduction and flexion direction; angles were below this value 10% of the time.
50th percentile posture	Median posture; angles were below this value half of measuring time and half time above.
90th percentile posture	Peak posture in the abduction and extension direction; angles were above this value 10% of the time.

* Two pause limits were evaluated, 5 and 10 °/s.

3.4.3.2 Electromyography.

For rejection of DC offsets, the sampled EMG signals were first digitally filtered with a 2nd-order Butterworth dual high-pass filter with a cut-off of 0.05 Hz using a program written in Labview™. The signals were then full wave rectified and averaged in 50-ms non-overlapping windows with the program MegaWin (Mega Electronics Ltd., Kuopio, Finland). Hence, averaged rectified values (ARV) EMG signals of 20 Hz were obtained which matched the 20 Hz sampling frequency of the goniometer signals. The signals were normalized relative to the MVEs, which were calculated as the maximal moving 1-s ARV value from the three maximal reference contractions (Mathiassen, 1995). A noise level for each subject was determined as the lowest moving 0.5-s ARV value. The noise level was subtracted, in a power sense, from the signal (Thorn et al., 2007).

The parameters of muscle activity for each subject were calculated using a program written in MATLAB® (MathWorks inc.; Natick, MA, USA). For each of the four muscles, five activity parameters were calculated; these are listed and described in Table 4. The 10th, 50th and 90th percentile of the muscle activity were calculated and used to describe static, median and peak levels respectively (Hagberg, 1979). Muscular rest was considered when muscle activity was below 1% MVE (Thorn et al., 2007). Muscular rest time was calculated from the ARV EMG signals using 0.1-s windows. Then the percentage of ARV-values below 1% MVE was computed as the relative muscular rest time. In that way a so called ‘gap’ in muscular activity had to last at least 0.1 s. Furthermore, the gap frequencies were calculated and expressed as number of gaps per minute.

Table 4. The EMG parameters listed and explained

EMG parameters; ED, APL, FDI and APB.	Explanation
10th percentile	Static load; only 10 % of measuring time muscle is under this load, 90% of time above this load.
50th percentile	Median load; half of measuring time the muscle is under this load and half time above.
90th percentile	Peak load; 90% of measuring time muscle is under this load, only 10% of time the above this load.
Relative rest time	Percentage of measured time when muscular load is below 1 % MVE.
Gaps frequency	Number of periods (gaps) of at least 0.1 s per minute when muscular load is below 1 % MVE.

3.4.3.3 Cross-correlation.

To estimate the temporal correlation of the synchronized goniometer and EMG ARV signals, cross-correlation functions were calculated for each set of data from each individual. This calculation means synoptically, that the two signals are multiplied time-step by time-step. Then, one of the signals is delayed one step and the two shifted signals are again multiplied, step by step. The signal is delayed further steps followed by multiplication and so forth. Finally, all these products are plotted as a function of the stepwise delay and the highest product is identified as the cross-correlation together with the corresponding time delay. A more strict explanation of cross-correlation can be found in literature. (Bendat and Piersol, 2000). Combinations of angle/EMG and angle velocity/EMG data for the two movement planes and the four muscles totally give 16 different pairs of goniometry and muscle activity data (Table 5).

Table 5. The 16 different combinations of goniometry and muscle activity data.

Goniometry		EMG	Goniometry		EMG
Angle	Flex/Ext	APB	Velocity	Flex/Ext	APB
	Ab/Ad			Ab/Ad	
	Flex/Ext	APL		Flex/Ext	APL
	Ab/Ad			Ab/Ad	
	Flex/Ext	ED		Flex/Ext	ED
	Ab/Ad			Ab/Ad	
	Flex/Ext	FDI		Flex/Ext	FDI
	Ab/Ad			Ab/Ad	

Normalized cross-correlation functions *R(d)* were computed for the combinations of goniometry and muscle activity data giving correlation coefficients. *R(d)* can range between -1 (strong negative correlation) and 1 (strong positive correlation) with d corresponding to the time delay between the two signals. A positive delay time indicates that EMG activity proceeded the movements registered by the electrogoniometer. For each subject, the maximum (*Rmax* +) as well as the minimum (*Rmax -)* of the cross-correlation functions and the corresponding delays *(d)* were computed and averaged over the 15 subjects. The highest group mean value (*Rmax*) of the two measures (*Rmax -, Rmax +)*, was presented along with the corresponding mean delay.

The 20 Hz ARV conversion introduces a delay of 0.025 s in the processed EMG data. In order to correctly analyze the goniometry and EMG signals, delays were introduced into the goniometry signals to synchronize the angle, angle velocity and EMG RMS data samples. The signals were also up-sampled to 200 Hz to increase the time resolution of cross-correlation functions and the mean from both signals was subtracted before the cross correlation was computed.

3.5 Statistics

3.5.1 WRIST AND THUMB GONIOMETRY ACCURACY – STUDY I, II & III

In study I, given the small sample size, the non-parametric Wilcoxon matched-pairs signed rank sum tests were performed to determine whether there were any differences in ROM and crosstalk measurements between the wrist goniometer systems over the various movement ranges and p-values were reported.

In study II, The fact that there are no non-parametric tests that can calculate both p-values and interactions on repeated measures, and the apparent normal distribution of the data (no outliers), repeated measures analysis of variance methods were used to determine whether there were significant differences between wrist goniometer systems, pronation/supination positions or any significant goniometer system by position interactions.

In study III, given the small sample size, non-parametric Wilcoxon sign rank tests were used to determine whether there were significant differences in thumb postural measurements between the manual and electrogoniometer measurements.

Results were considered to be statistically significant when p-values were ≤ 0.05.

3.5.2 FEASIBILITY OF THUMB ELECTROGONIOMETRY – STUDY III

Wilcoxon sign rank tests were also used to determine whether there were any significant differences in the postural measures between the thumb postures when using the two mobile phones in the laboratory task. In addition, non-parametric Spearman Rho correlation coefficients were calculated in order to determine whether there was any correlation between the thumb postures when operating the two phones. Results were considered to be statistically significant when p-values were ≤ 0.05.

3.5.3 THUMB ELECTROGONIOMETRY AND EMG ASSOCIATIONS – STUDY IV

For determination of the association between thumb posture and muscular load, two analysis methods were used: Group correlations comparing signal group means and cross correlations, the temporal correlation of each individual’s synchronized goniometer and EMG signals.

3.5.3.1 Group correlations between goniometry and EMG parameters

The degree of association between the various goniometry and EMG summary measures were analyzed using the parametric Pearson Product-Moment correlation coefficient (Altman, 1991) and calculated with the statistical software JMP® (SAS Institute; Cary, NC, USA).

Correlations greater than 0.60 were tabulated and subjected to further analysis. This correlation threshold was regarded as being strong enough for practical purposes and gives for n = 15 a p-value less than 0.02 (Altman, 1991).

3.5.3.2 Cross correlations between goniometry and EMG signals

The maximal correlation and the corresponding delay between the two signals being compared were tabulated for each subject and muscle-angle combination, and averages across the group were calculated. Then group mean maximal cross-correlation values which were above 0.2 were subjected to further analysis. In signals with a cross-correlation above 0.2, a temporal match between signals can be seen when plotted against time. The p-values for individual maximal cross-correlations may be estimated by using the number of “uncorrelated” samples (which in turn may be estimated from the signals’ autocorrelation functions and length). For individual cross-correlation above 0.2 in this experiment, where all signals were longer than 124 s, the p-value would always be less than 0.02. For group means above 0.2 the p-value the significance would be even greater.

4 RESULTS

4.1 Wrist goniometry accuracy – Study I & II

4.1.1 DIFFERENCES BETWEEN SYSTEMS: 90º PRONATION - STUDY I

4.1.1.1 Measurement errors

There were important differences between the two goniometer systems in the measurement of wrist position. Departures from the movement matrix (Gold Standard) indicate measurement errors. System A both overestimated and underestimated F/E, which was dependent on the amount of R/U deviation (Figure 10 left). R/U deviation was also sensitive to the amount of F/E and could either be overestimated or underestimated depending on the amount of F/E. System B's F/E data was slightly offset with a tendency toward overestimating extension (Figure 10 right). In 90º pronation, System B, unlike System A, was less prone to errors in both F/E and R/U deviation across the various positions tested.

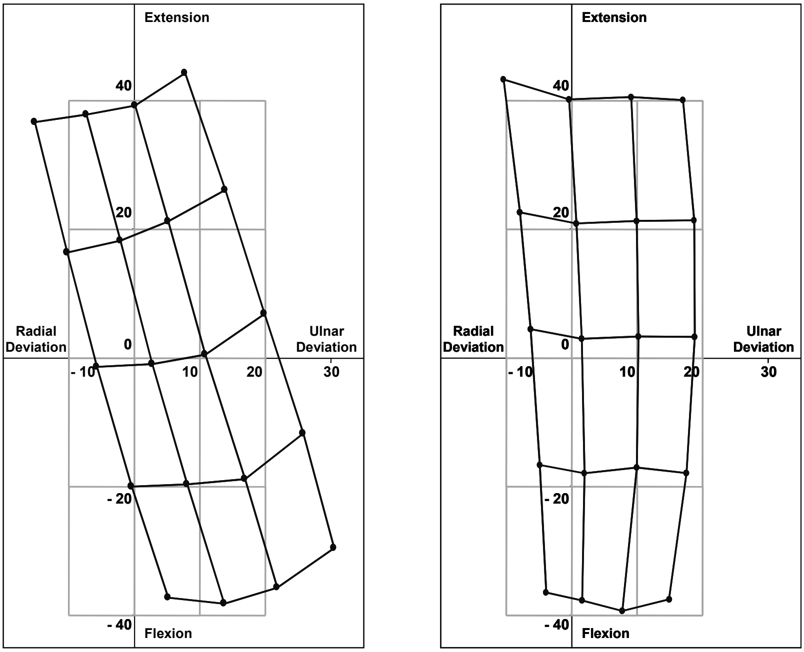


Figure 10. Movement Matrixes, wrist in 90º pronation. System A (left), System B (right). Results for the 20 different wrist positions tested relative to the Gold Standard movement matrix (grey lines– the actual wrist positions controlled by wrist positioning apparatus fixture).

4.1.1.2 Range of movement and crosstalk measurement

The performance of both goniometers was similar for measuring the various F/E ROM movements (Table 6). With both systems, F/E ROMs were slightly underestimated. However, there were differences in the amount of R/U crosstalk associated with the various F/E movements. With System A, on average, there was a 5.3º change in the R/U angle (R/U Crosstalk) with every 20º of F/E; with System B, the change in R/U angles was smaller, averaging 0.7º (Table 6).

Also the R/U ROMs were similar and underestimated (Table 7). Slight differences existed in the amount of F/E crosstalk with respect to the various R/U movements. With System A, on average there was a 2.8º change in the F/E angle (F/E crosstalk) with every 10º of R/U deviation; with System B, the change in F/E angles was less, averaging 0.6º (Table 7). In general, the upper and lower limits of the R/U ROM movements, the ranges, were smaller with System B (table 7).

Table 6. Measured ROM in flexion/extension and corresponding radial/ulnar deviation crosstalk[a]. Mean and (ranges) in degrees shown in table. (*n* = 8)

		Measured flexion/extension ROM			Radial/Ulnar Crosstalk		
Movement	**ROM**	**System A**	**System B**	**p-value**	**System A**	**System B**	**p-value**
- 40° to -20° Flexion	**20**	18.5 (14.4 – 24.3)	19.7 (14.8 – 23.0)	0.18	-5.7 (-7.3 – -3.6)	0.3 (-3.2 – 3.1)	0.0009
- 20° to 0° Flexion	**20**	18.7 (15.3 – 22.5)	20.9 (16.8 – 25.8)	0.27	-5.3 (-9.0 – -1.8)	-0.4 (-1.6 – 0.5)	0.0009
0° to 20° Extension	**20**	19.2 (15.75 – 25.2)	17.9 (12.2 – 25.1)	0.31	-4.9 (-9.0 – -1.8)	-0.8 (-3.2 – 0.4)	0.001
20° to 40° Extension	**20**	19.6 (10.8 – 25.2)	19.3 (11.0 – 23.2)	0.87	-5.2 (-11.7 – 0.0)	-1.1 (-6.7 – 1.7)	0.03
-40° to 40° Full ROM	**80**	76.0 (68.4 – 84.6)	77.8 (72.5 – 82.8)	0.56	-21.0 (-33.3 – -9.0)	-2.0 (-6.0 – 1.7)	0.0009

[a] Negative radial/ulnar crosstalk values indicate a false radial deviation signal, positive values a false ulnar deviation signal. Wrist in 90° pronation.

Table 7. Measured ROM in radial/ulnar deviation and corresponding flexion/extension crosstalk[b]. Mean and (ranges) in degrees shown in table. (*n* = 8)

		Measured radial/ulnar ROM			Flexion/Extension Crosstalk		
Movement	**ROM**	**System A**	**System B**	**p-value**	**System A**	**System B**	**p-value**
- 10° to 0° Radial	**10**	8.4 (3.6 – 15.3)	7.8 (4.7 – 13.6)	0.87	0.5 (-1.8 – 3.6)	-1.5 (-3.0 – 0.8)	0.04
0° to 10° Ulnar	**10**	8.1 (4.5 – 15.3)	8.7 (6.2 – 13.7)	0.63	1.5 (-1.8 – 5.4)	0.3 (-3.6 – 6.5)	0.31
10° to 20° Ulnar	**10**	9.0 (2.7 – 12.6)	8.6 (5.2 – 10.1)	0.43	6.3 (0.0 – 10.8)	-0.1 (-2.4 – 3.1)	0.005
- 10° to 20° Full ROM	**30**	25.6 (16.2 – 34.0)	25.1 (21.6 – 31.7)	0.63	8.2 (-3.6 – 13.5)	-1.2 (-7.3 – 2.8)	0.01

[b] Negative flexion/extension crosstalk values indicate a false flexion signal, positive values a false extension signal. Wrist in 90° pronation.

4.1.2 DIFFERENCES BETWEEN SYSTEMS: THE EFFECTS OF PRONATION AND SUPINATION - STUDY II

4.1.2.1 Radial/ulnar crosstalk

When the wrist was moved from extension to flexion there was a change in the radial/ulnar component of the wrist angle (Figure 11). System A was prone to more R/U crosstalk than System B. With System A, the R/U crosstalk was largest in 90 P, lowest in 0 N and increased, but in the opposite direction, in 45 S. With System B, the R/U crosstalk was relatively constant over the various P/S positions. (Figure 11 and Table 8)

4.1.2.2 Flexion/extension crosstalk

When the wrist was moved ulnarly to radially, there was a change in the F/E component of the wrist angle (Figure 11). F/E crosstalk was present with both goniometer systems. The F/E crosstalk tended to be parabolic shaped with System A and was greatest in 90 P, decreased in 45 P and 0 N and increased but in the opposite direction in 45 S. With System B, the F/E crosstalk gradually increased from 90 P to 45 S. (Figure 11 and Table 8)

4.1.2.3 Offset errors

Offset errors were minimal in the 90 P position, the position the goniometers were calibrated/zeroed in, and in general offset errors increased the further away the P/S position was from the calibration position (Figure 11). Depending on the pronation/supination position, both goniometer systems tended to overestimate the amount of extension. In general, System B was prone to greater F/E offset errors but followed the same trends as System A. For both systems, F/E offset errors were at a maximum in 0 N and R/U offset errors maximal in 45 S. R/U offset errors were roughly equal but opposite in direction between the two goniometer systems as can be seen in Figure 11. The offset errors are summarized in Table 8.

4.1.2.4 Range of movement

Both systems tended to underestimate F/E ROM, and to a greater extent, R/U ROM movements over the various pronation/supination positions tested (Table 8).

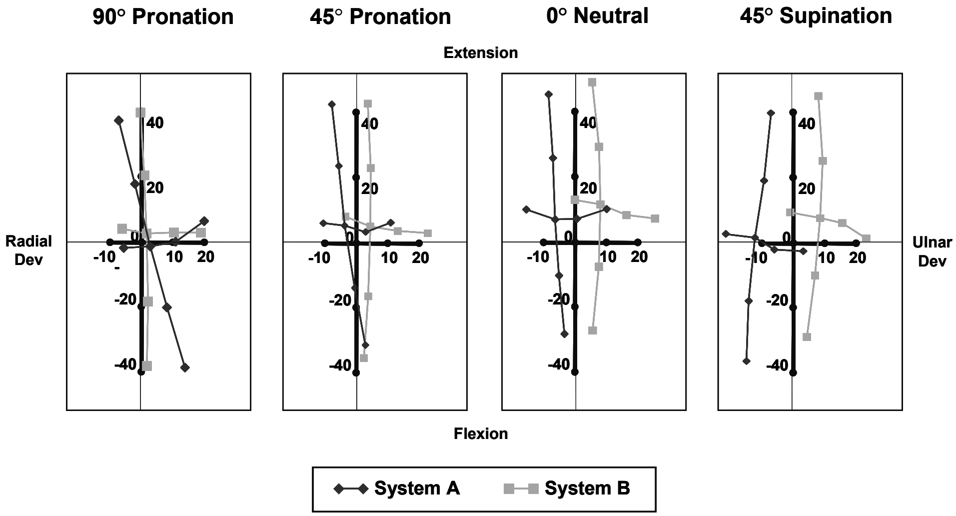


Figure 11. The effects of pronation and supination on measurement accuracy. The bold black identity lines indicate the actual movements according to the "Gold Standard"; the dark grey lines with the diamonds, the angle measurements from System A; and the light grey lines with squares, the angle measurements from System B. Departure from the bold vertical and horizontal identity lines indicates the presence of R/U and F/E crosstalk respectively. The horizontal and vertical distances from the origin of the identity lines to the intersection point of the goniometry data represent F/E and R/U offset errors respectively. The data shown from System A and B are group means from the 8 subjects.

Table 8. Crosstalk, offset errors and range of movement (ROM), grouped by goniometer system, over the pronation/supination positions tested[c]. Direction of movement was from 40º flexion to 40º extension and 10º radial deviation to 20º ulnar deviation (*n*=8). The p-values under systems and positions indicate the differences between goniometer systems and between pronation/supination positions. The interaction p-values indicate performance differences between the goniometer systems across the range of pronation/supination positions tested.

	System A				System B				p-values		
	90 P	45 P	0 N	45 S	90 P	45 P	0 N	45 S	Systems	Positions	Interactions
R/U Crosstalk (-40º to 40º)	-21.0	-11.4	-4.9	7.9	-2.8	0.2	-0.2	5.0	0.03	<0.01	<0.01
F/E Crosstalk (-10º to 20º)	8.6	0.9	1.2	-8.1	-0.8	-5.5	-7.2	-9.2	0.01	<0.01	0.10
F/E Offset Error	-0.9	6.3	8.7	1.5	3.1	6.0	13.0	8.5	<0.01	<0.01	0.01
R/U Offset Error	2.7	-3.0	-5.1	-11.6	1.6	3.8	8.1	9.0	<0.01	0.04	<0.01
F/E ROM (80º)	76.0	73.8	73.8	76.0	77.8	78.1	76.5	73.9	0.52	0.36	0.24
R/U ROM (30º)	25.6	26.8	25.3	24.4	25.1	28.4	25.2	24.0	0.58	0.31	0.25

[c] Negative radial/ulnar (R/U) crosstalk and offset error values indicate a false radial deviation signal. Negative flexion/extension (F/E) crosstalk and offset error values indicate a false flexion signal.

4.2 Thumb goniometry accuracy – Study III

There were small differences between the manually measured angles and the electrogoniometer both for reference positions (table 9) and for maximal thumb positions (table 10). For the reference positions, the greatest mean and mean absolute errors were in Flex/Ext, at 2.3˚ and 3.6˚, respectively. For the maximal thumb positions, the greatest mean errors were 4.4˚ (Flex/Ext) and 3.7˚ (Ad/Ab), representing 9.4% (4.4º / 46.7º) and 12.6% (3.7º / 29.3º) of the thumb's range of motion in each movement plane, respectively.

Table 9. Measurement accuracy in the five reference positions and absolute differences between the position the thumb was placed in using the manual goniometer and the measured angle registered by the electrogoniometer (*n*=15).

		Measured angle (º) using electrogoniometer				
Movement	Reference position	Mean (SD)	Range	Difference (˚)	*p*-value	Absolute difference (˚)
Ad/Ab	20˚	19.2 (3.2)	14.5 to 24	0.8	0.39	2.8
	0˚	-0.4 (2.8)	-6.0 to 5.0	0.4	0.77	2.0
Flex/Ext	- 20˚	-18.3 (4.2)	-25.8 to -11.0	-1.7	0.09	3.6
	0˚	-1.2 (3.3)	-7.0 to 3.2	1.2	0.26	2.5
	40˚	42.3 (4.0)	36.7 to 50.6	-2.3*	0.04	3.2

* Indicates statistically significant difference.

Ad/Ab = adduction/abduction; Flex/Ext =flexion/extension.

Table 10. Measurement accuracy in the neutral adduction/abduction (Ad/Ab) and maximal voluntary thumb positions (relative to the manual goniometer measurements) and absolute differences between the angles measured with the manual goniometer and electrogoniometer (*n*=15).

	Manual goniometer measured angle (º)		Electrogoniometer measured angle (º)				Absolute
Movement	Mean (SD)	Range	Mean (SD)	Range	Difference (˚)	*p*-value	difference (˚)
Neutral Ab/Ad	0	0	-0.4 (2.8)	-6.0 to 5.0	0.4	0.77	2.0
Max abduction	29.3 (4.6)	22 to 39	33.0 (8.1)	21.7 to 50.8	-3.7	0.12	4.9
Max flexion	-46.7 (9.6)	-60 to -27	-42.3 (10)	-61.0 to -23.1	-4.4*	0.03	6.2
Max extension	56.1 (6.1)	43 to 64	57.7 (7.7)	44.0 to 69.0	-1.7	0.39	5.6

* Indicates statistically significant difference.

4.3 Feasibility of thumb electrogoniometry – Study III

When results were compared between subjects entering a 300 character SMS message using their own mobile phone and the standard mobile phone, there were some differences in Ad/Ab postures and movement velocities but no significant differences in MPFs (repetitiveness), Flex/Ext parameters or task completion times (table 11). Across subjects, postures and velocities were highly correlated when using the two mobile phones. There were systematic postural differences between mobile phones; subjects had significantly more abduction and slightly less adduction when using the standard phone. Thumb movements with the standard phone were faster in Ad/Ab (p=0.03) but similar in Flex/Ext (p=0.43). When comparing movement planes, velocities were over two-fold higher in Ad/Ab compared to Flex/Ext and spanned a greater range of motion. When subjects used their own phone, abduction and flexion movements were 79% (= 26.2˚ / 33.0 ˚) and 55% (= -23.2˚ / -42.3 ˚) of the thumb's maximal range in each direction, respectively.

Table 11. Differences and correlations between measurements when using own mobile phone and standard mobile phone for thumb positions, angular velocity, mean power frequency (MPF) and time to enter a 300 character SMS message (*n*=10).

		Mobile phone:					
Position	Measurement parameter[d]	Own Mean (SD)	Standard Mean (SD)	Difference	Difference *p*-value	Correlation	Correlation *p*-value
Ad/Ab	5th percentile (º)	-6.3 (14.8)	-2.5 (14.9)	-3.8*	0.04	0.95*	<0.0001
	50th percentile (º)	9.4 (16.1)	15.9 (12.0)	-6.5*	0.04	0.85*	0.002
	95th percentile (º)	26.2 (14.4)	32.5 (13.7)	-6.3*	0.02	0.73*	0.02
	Velocity (º/s)	26.1 (10.3)	30.5 (10.3)	-4.4*	0.03	0.88*	0.0008
	MPF (Hz)	0.47 (0.08)	0.52 (0.08)	-0.05	0.27	0.21	0.56
Flex/Ext	5th percentile (º)	-23.2 (8.1)	-21.6 (9.8)	1.6	0.62	0.87*	0.001
	50th percentile (º)	-16.0 (8.7)	-14.1 (10.4)	1.9	0.36	0.89*	0.0006
	95th percentile (º)	-6.4 (10.1)	-5.4 (10.6)	1.0	0.77	0.85*	0.002
	Velocity (º/s)	13.4 (4.0)	14.1 (3.2)	-0.7	0.43	0.81*	0.005
	MPF (Hz)	0.46 (0.10)	0.50 (0.08)	-0.04	0.32	0.22	0.53
Task completion Time (s)		201.8 (36.6)	201.6 (53.3)	0.2	0.99	0.36	0.31

* Indicates statistically significant differences and significant correlations.

[d] The 5th percentile angle represented extreme adduction and flexion posture, 50th percentile median posture and the 95th percentile extreme abduction and extension.

4.4 Thumb electrogoniometry and EMG associations – Study IV

4.4.1 GROUP CORRELATIONS BETWEEN GONIOMETRY AND EMG

Of the four investigated muscles, the muscle activity of the ED (extensor digitorum communis) and FDI (first dorsal interosseus) had the strongest associations to thumb postures and movements (Table 12).

The 10th percentile Ad/Ab angle was negatively correlated with static ED muscle activity
(r = -0.80). Thus, subjects with higher peak adduction (negative values, therefore negative correlation) had higher static muscle load in the ED (figure 12). In addition, the peak velocity in the adduction/abduction plane was associated with static ED muscle activity (r = 0.69). This indicates that high thumb movement velocities in the abduction/adduction plane demands a high stabilizing role of the ED muscle.

The 10th percentile flex/ext angle was correlated with static FDI muscle activity (r = 0.69). This indicated that subjects with less peak flexion, whose thumbs were more in a neutral posture, had higher static muscle load in the FDI, which means that the stabilizing role of the FDI muscle was more pronounced. This is consistent with the observation that for subjects with more peak flexion, the proportion of muscular rest in the FDI was greater (r = -0.61) and the number of FDI gaps per minute increased (r = -0.81). For subjects with shorter pauses for flexion/extension movements, peak muscle load tend to be higher (r = -0.68).

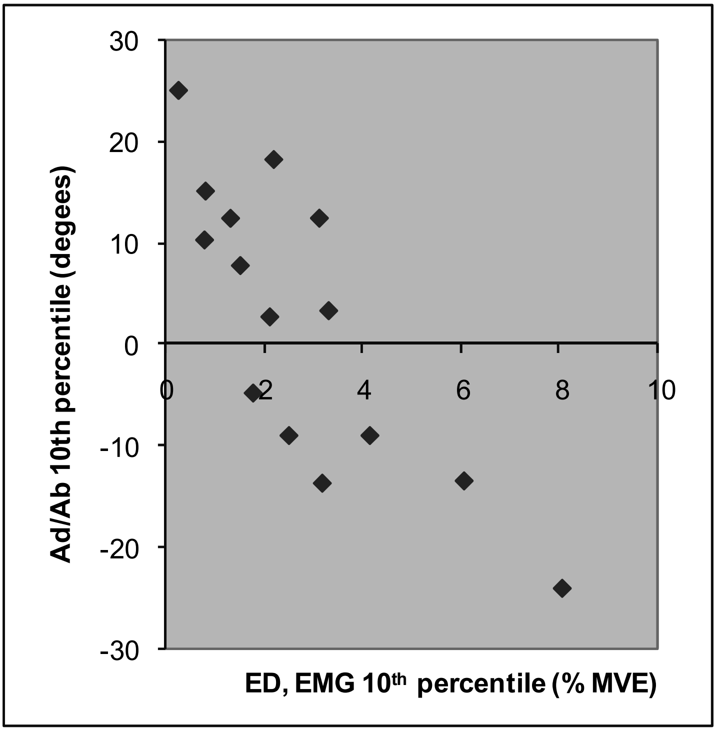
For the intrinsic and extrinsic muscles of the thumb, APB (abductor pollicis longus) and APL (abductor pollicis brevis) respectively, only two associations between thumb goniometry and muscle activity were seen: Subjects with higher peak velocities in the adduction/abduction plane tended to have higher static APB muscle activity (r = 0.62) and subjects with a more adducted thumb tended to show higher peak APL muscle
loads (r = -0.65).

Table 12. Group correlation coefficients above 0.6 between the EMG and thumb goniometry parameters (*n* = 15).
In cases where more than one goniometric measure was correlated with muscle activity, subsequent correlations are shown in parentheses.

Muscle	Goniometer		Correlation	Association	Interpretation
	Movement	Measure			
ED	Ad/Ab	Posture	-0.80	Static muscle load and 10th percentile ad/ab angle	ED muscle load tends to be higher for subjects with high peak thumb adduction (and with high median ad/ab angle).
			-0.81 (-0.66)	Median muscle load and 10th and (50th) percentile ad/ab angle	
			-0.71 (-0.62)	Peak muscle load and 10th and (50th) percentile ad/ab angle	
		Velocity	0.64 (0,69)	Static muscle load and 50th and (90th) percentile ad/ab velocity	ED static muscle load tends to be higher for subjects with high median thumb ad/abduction velocities (and with high peak ad/abduction velocities).
FDI	Flex/Ext	Postures	0.69 (0.61)	Static muscle load and 10th and (50th) percentile flex/ext angle	FDI static muscle load tends to be higher for subjects with low peak flexion (and with low median flex/ext angles)
			-0.61	Muscle rest percentage and 10th percentile flex/ext angle	FDI muscle rest and gap frequency tends to be higher for subjects with high peak flexion angles (Gap frequency correlate with all three flex/ext percentiles).
			-0.81 (-0.79,-0.75)	Muscle gaps frequency and 10th and (50th, 90th) flex/ext angle	
		Velocity	-0.68	Peak muscle load and flex/ext pause mean duration*)	FDI peak muscle load tends to be higher for subjects with shorter flex/ext pause durations.
APB	Ad/Ab	Velocity	0.62	Static muscle load and 90th percentile ad/abduction velocity	APB static muscle load tends to be higher for subjects with high peak ad/ab velocities.
APL	Ad/Ab	Posture	-0.65	Peak muscle load and 10th percentile ad/ab angle	APL peak muscle load tends to be higher for subjects with high peak adduction.

*) A pause means that the thumb angle velocity is below 10º/s .

Figure 12. Example of thumb posture plotted against EMG activity (*n* = 15). For subjects with thumbs more towards adduction (negative values) higher ED muscular activity were seen. Correlation coefficient r = - 0.80.



4.4.2 CROSS-CORRELATIONS BETWEEN GONIOMETRY AND EMG

The average maximal cross-correlation value *Rmax* (absolute Rmax) for the 16 EMG- goniometer signal combinations were 0.20 (median 0.17). This indicates a low cross association in most cases. However, as shown in Table 13, three combinations yielded group mean Rmax values above 0.2.

Table 13. Notable cross correlations between EMG ARV and goniometric signals. The group mean of the maximum cross-correlation (Rmax) and its corresponding time delay (d) in seconds. Only group mean Rmax values above 0.2 are presented (*n* = 15). A positive delay indicates that EMG activity precede the goniometric activity.

Muscle	Goniometer		Rmax mean	Delay (s)	Interpretation
	Movement	Measure			
ED	Ad/Ab	Posture	0.21	0.00	ED muscle activity is associated with changes in adduction/abduction angle.
APB	Ad/Ab	Posture	0.51	0.13	APB muscle activity is associated with changes in adduction/abduction angle. The muscle activity precedes the movements by 0.13 seconds.
		Velocity	0.52	- 0.01	APB muscle activity is associated with changes in adduction/abduction movement velocities. The estimated delay between the two signals is close to zero.

As an example of strong positive cross-correlation, figure 14 shows the R(d):s for all 15 subjects for the APB EMG ARV signal and goniometer ad/ab angle velocity combination. The APB signal showed mean Rmax cross-correlations above 0.5 both with thumb ad/ab angle and ad/ab angle velocities. The inter-individual variability for the maximal cross correlation (Rmax) and time delay is given in Table 14. The temporal association of these two signals was obvious also when the signals were plotted next to each other versus time. Figure 14 shows an example of temporal traces of EMG and angle velocity from one subject whose Rmax was 0.58 and the associated time delay close to zero.

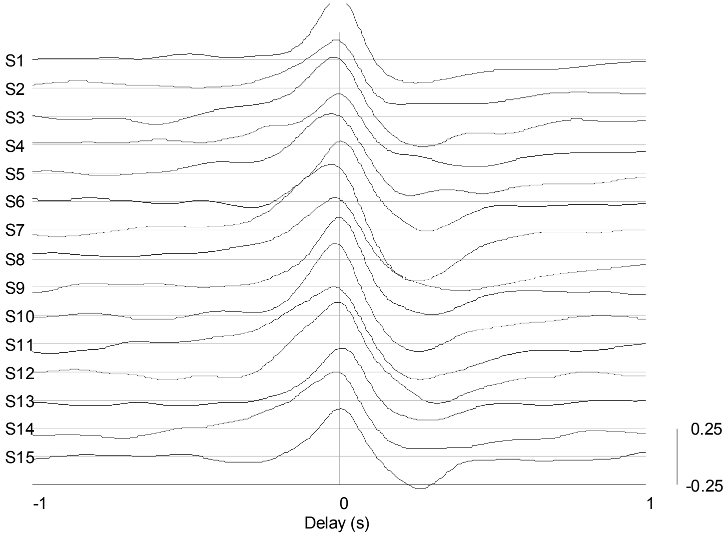


Figure 13. APB EMG ARV and ad/ab angle velocity cross-correlations for the 15 subjects showing R(d) for the delay from –1 to 1 s. For a positive delay, the EMG signal precedes the goniometric signal. As seen in figure, for this muscle/velocity combination, the maximum cross-correlations occur when the delay between signals is close to zero seconds, the magnitude of the cross correlation is shown to the right of the graph. Example: For subject 7, Rmax = 0.58 with a time delay of -0.03 s.

Table 14. The mean, median and range of individual maximal cross correlations (Rmax) and time delays for APB EMG ARV and Ad/Ab goniometric signals. *n* =15.

	Cross correlation APB vs Ad/Ab			
	Angle		Velocity	
	Rmax	Delay (s)	Rmax	Delay (s)
Mean	0.51	0.13	0.52	- 0.01
Median	0.51	0.12	0.53	- 0.01
Min	0.30	0.10	0.42	- 0.03
Max	0.76	0.16	0.63	0.01

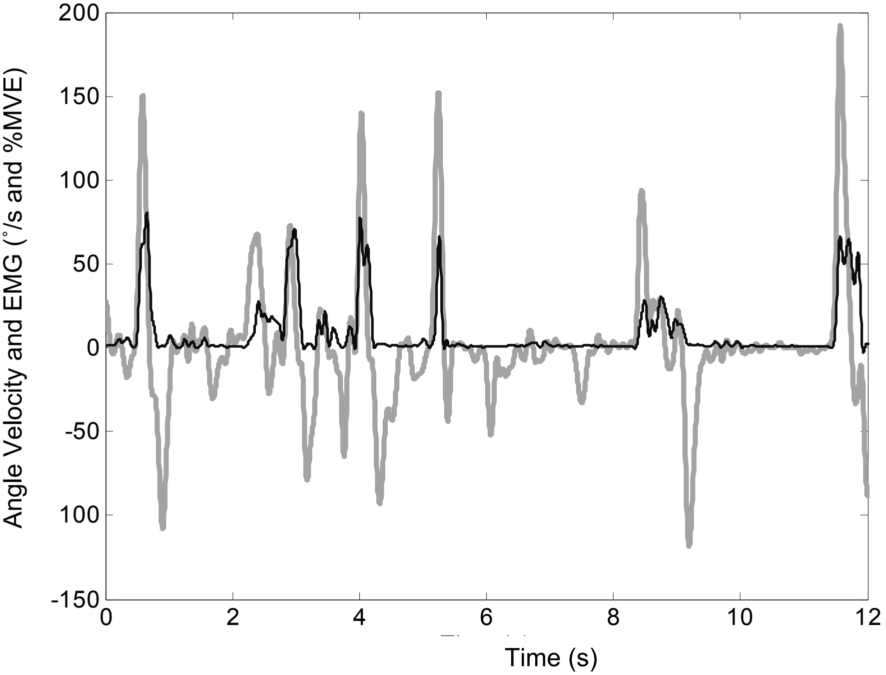


Figure 14.
Traces of APB EMG ARV (black thin line) and ad/ab thumb angle velocity (gray thick line) for Subject 7. As indicated in figure 13, cross-correlation Rmax was 0.58 with a time delay close to zero (- 0.03 s).

5 DISCUSSION

The thesis may be used to help direct future studies to further the understanding of wrist and thumb joint measurements and eventually lead to improvements in goniometer design, use and application.

This thesis was a part of a larger project with a principal objective of identifying risk factors that may be associated with the use of hand-held ICT devices. (Gustafsson, 2009), (Gustafsson et al., 2009), (Thomée et al., 2007), (Wahlström et al., 2004), (Gustafsson and Hagberg, 2003), (Lindegard et al., 2003), (Wahlström et al., 2003), (Wahlström et al., 2002), (Wahlström et al., 2000).

5.1 Wrist goniometry accuracy – Study I & II

It appears that the goniometer design, the linear alignment algorithm employed with System B as well as transducer placement are all possible explanations for the observed errors and differences between the two goniometer systems. Evaluation of wrist posture can be facilitated by using either of the goniometer systems but knowing the limitations of each system will be important in the context of interpreting results. Some additional standardization in the use of goniometers would facilitate comparisons within and between studies when different methods or equipments are used. For example, how neutral wrist positions are defined and the pronation/supination position chosen to calibrate/zero the goniometers are important considerations when comparing results.

With System A, the trends in the differences from the "Gold Standard" were similar to the results shown in (Buchholz and Wellman, 1997); however, the R/U crosstalk was greater in our study. A one-to-one comparison of System A's results is difficult due to the use of a differently sized goniometer and different calibration posture.

The main finding is that forearm pronation/supination will affect wrist angle measurements such as the magnitude and direction of measurement errors. There were both similarities and differences in measurement accuracy and error patterns between goniometer systems, the combination of these similarities and differences may lead to improvements in goniometer design and application.

5.1.1 DESIGN DIFFERENCES BETWEEN GONIOMETER SYSTEMS

1) System A has a resolution of 1.8° and system B has 0.1°. If measurements were made on just one individual, then this difference in resolution would have an impact when comparing individual results. However, since the measurements were calculated and averaged over eight subjects, the arithmetic process used to derive mean values resulted in an effective resolution of 0.2° for System A. Thus, the

differences in resolution should not be important to the differences observed between goniometer systems in this study.

2) The single-transducer used with System A was firmly attached with double-sided tape to the hand and forearm and could not be moved after the transducer had been zeroed. Subsequently, if the endblocks of the transducer were twisted due to wrist movement, crosstalk could occur (Hansson et al., 1996) (Buchholz and Wellman, 1997). With System B, the proximal ends of the transducers floated freely within the proximal endblocks, this allowed the endblocks to twist without imparting any twist on the transducers. Based on the known relationship between goniometer twist and crosstalk (Hansson et al., 1996), the twist reducing design of System B may be a major factor behind the differences in R/U crosstalk between the systems. In addition, System B's fingerless glove system allowed the proximal endblock to freely slide over the skin of the forearm, this to reduce the movement artefacts associated with skin and/or bone movement under the endblocks that may occur during pronation/supination.

3) System B employed a 5-point calibration providing specific gains to each subject and a algorithm to correct and compensate for crosstalk as described in the Methods. It seems that this algorithm played a minor role in reducing crosstalk but has been shown to reduce between subject variability.

4) System A had a single transducer for measuring wrist angles whereas System B employed two transducers. Due to using the same transducer for measuring both F/E and R/U deviation, the design of System A assumes that the axes for F/E and R/U deviation are orthogonal and intersect one another. However, there is evidence that the wrist has two, non-orthogonal, non-intersecting axes of movement (Youm and Yoon, 1979); (Moore et al., 1993); (Van Vorhis, 1996). One implication for System A is, if goniometer twist was present and somehow optimised relatively to one movement axis, this optimisation may not apply or could be detrimental to the other movement axis. System B with its two-transducer design attempts to locate the transducers over and orthogonal to the two different movement axes, thereby making the transducer optimisation independent, and potentially reducing crosstalk and measurement errors associated with transducer placement. This could also explain some of the observed differences in performance between the systems.

5.1.2 CROSSTALK

There are three sources of crosstalk: 1) crosstalk associated with the engineering design of the goniometer – the twisting of the goniometer transducers when the wrist and/or forearm is moved away from neutral. 2) crosstalk associated with the location of the goniometer transducers relative to joint centres of movement - the need for the orthogonal application of the goniometer transducers relative to wrist axis of movement, and 3) crosstalk associated with changes in surface anatomy of the forearm during pronation and supination - the surface of the forearm under the goniometer changing shape causing a false signal (crosstalk) in one or both movement planes.

Based on the results from (Hansson et al., 1996), it appears that the majority of the R/U crosstalk measured with System A was due to the twisting of the goniometer transducer. The differences in means between goniometer systems on left side of Figure 15 may be a function of the differences in the amount of transducer twist.

Both goniometer systems were subject to crosstalk measurement errors with the errors being a function of P/S position. The amount of crosstalk errors will also affect angular velocity and acceleration measurements which will be dependent on the goniometer system chosen. System A was prone to more R/U crosstalk compared to System B. The position 90º P, near full wrist pronation, could be considered to represent the extreme for System A as far as R/U crosstalk results are concerned. F/E crosstalk was present with both goniometer systems and was also shown to vary with P/S position. However, with both systems, these F/E crosstalk errors were smaller and less problematic.

Figure 16 shows the results from the four pronation/supination positions, grouped by goniometer, superimposed over one another and aligned to the origin. With System A, there was a synchronous clockwise shift in both the F/E and R/U movements going from 90 P to 45 S and the result indicates that this shift in the signal was due to the known rotation of the endblocks that occurs with pronation and supination (Hansson et al., 1996). However, with System B, there was very little shift in the F/E movements and a slight clockwise shift in the R/U movements. This difference between the goniometer systems can be attributed to two of the design differences. First, unlike System A, System B allowed the endblocks to twist/rotate without twisting the transducers. Second, unlike System A, System B’s fingerless glove allowed the endblocks to move freely over the forearm. However, based on the present study, it is not possible to determine the relative importance of each of these design features.

System B used a linear algorithm to “electronically align” the goniometers during the five-point calibration procedure to correct for crosstalk. Besides the twist reducing design above, the feeling is that the algorithm can measure and correct for some remaining misalignment in the transducer, considering individual differences. This difference between the systems is represented by the differences in individual variation (standard deviation) on right side of Figure 15. Finally, the algorithm was derived in the calibration position (90 P) and could propagate errors to the other P/S positions. This was not the case for the F/E identity movements, which did not shift/rotate with P/S, but the R/U identity movements did, as shown in Figure 16. This shift/rotation of the R/U movements could be the result of a propagation of errors from the electronic alignment algorithm or due to a mechanical artefact from P/S. Further work has to be done to identify the importance of the alignment algorithm.

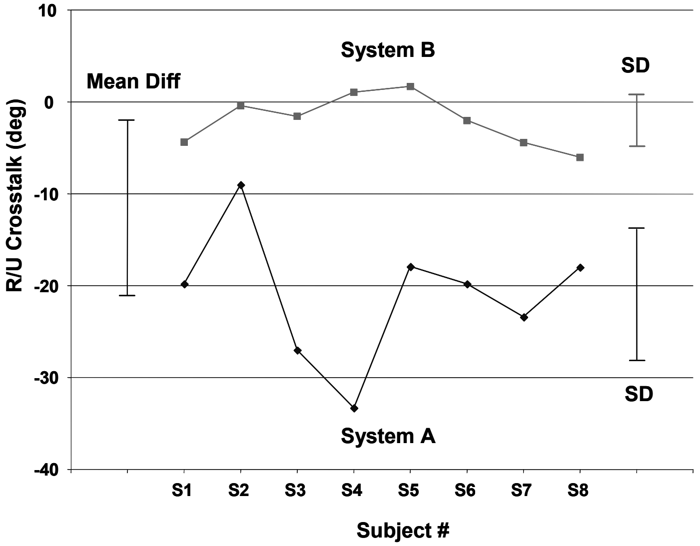


Figure 15. Individual comparison of R/U Crosstalk between System A and B over the full range of F/E in 0° R/U and 90° P grouped by subject. The mean difference between systems is shown on the left, and using the group standard deviation, individual differences within systems are shown on the right.

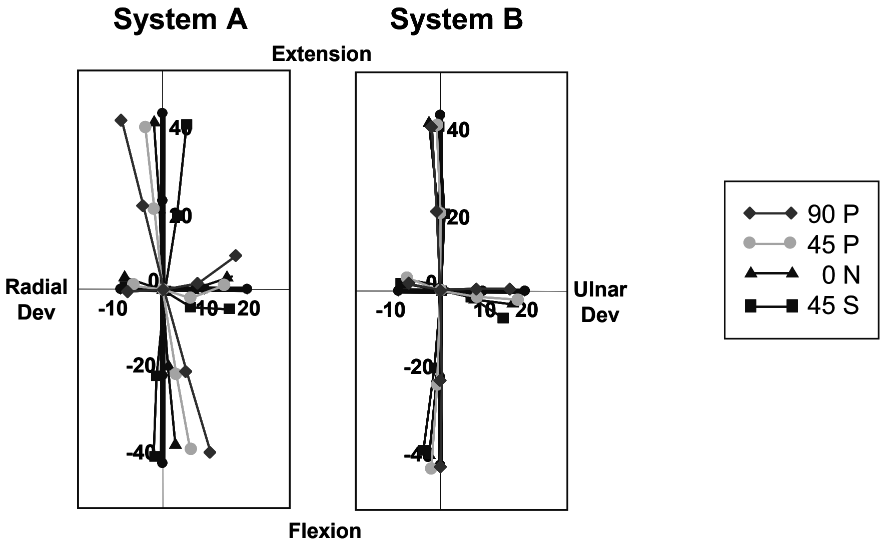


Figure 16. The effects of pronation and supination on F/E and R/U crosstalk grouped by goniometer system. Offset errors in the various pronation and supination positions have been corrected for, so the origins in each P/S position are aligned (*n*=8).

5.1.3 OFFSET

Both goniometer systems were subject to both R/U and F/E offset errors, with the errors being a function of P/S position (Figure 11, Table 8). These errors may be due to changes in the cross-sectional shape of the forearm that occur with P/S. F/E offset errors were similar between the goniometer systems in both magnitude and direction. However, R/U offset errors were roughly equal in magnitude but opposite in direction. The R/U transducer on System B was situated more radially compared to System A. This indicates that a more intermediate placement of the R/U transducer may be optimal for reducing R/U offset errors.

The offset errors tended to increase as the wrist and forearm moved away from the P/S position the goniometers were calibrated/zeroed in. When the goniometers were calibrated in 90º P, the offset errors were minimal in 90º P and maximal in 0º N for F/E and in 45º S for R/U deviation. However, if the goniometers were calibrated in 0º N, the opposite would be the case. These results indicate that offset errors are a function of P/S position and will be affected by the calibration position. Therefore, to reduce measurement errors, it is critical that the goniometer is calibrated/zeroed in the P/S posture most likely to be encountered during measurement.

Finally, it is worth noticing that offset errors will affect position data, but other measurements like velocities, acceleration and mean power frequency measurements should be less affected as long as the wrist's P/S position is not changing during R/U and F/E movements.

5.1.4 RANGE OF MOVEMENT

Both systems underestimated ROM in both F/E and R/U and the magnitudes of the underestimation between the systems were similar (Table 8). Possible sources for the measurement errors include the equipment or methods used. One major difference between the goniometer systems was that System A had a fixed gain for measuring F/E and R/U, whereas System B had gains specific to each subject, which were derived from the 5-point calibration procedure. Therefore it would be reasonable to expect that System B would be more accurate than System A for measuring the ROMs. However, as shown by the range of motion measurements in Tables 6 and 7, the magnitude of the ROM measurements were similar, but System B tended to yield less between-subject differences with respect to the ranges of the R/U ROM measures, probably due to the subject specific gains. Since both systems yielded similar ROM measures, indicating that our procedures were relatively consistent between goniometers and between movement ranges (20° of F/E and 10° of R/U deviation), the ROM underestimation may primarily be due to the methods used. The underestimation in F/E and R/U deviation ROM can be explained by the fact that when the subjects were moving in F/E and R/U deviation, it was very easy for the subjects to slightly move the distal part of the forearm in the same direction of the movement, resulting in an underestimation of the ROM.

5.2 Thumb goniometry accuracy – Study III

The study demonstrated, that in a controlled laboratory setting, electrogoniometers can be used to accurately measure thumb Ab/Ad and F/E postures. In the experiment, measuring fixed reference positions of the thumb, group mean errors were below 1º for the measurement of Ad/Ab and below 3º for F/E measurements (Table 9). When maximal thumb positions were measured, the group mean errors were below 4º for Ad/Ab and 5º for F/E (Table 10). This accuracy is sufficient for clinical purposes. As for the wrist measurements above, sources for these measurement errors can be methodological and/or instrumentational. Methodologically, it was hard to visually repeat and measure the desired postures with manual goniometry. On the instrumentation side, twisting of the electrogoniometer end blocks relative to one another, skin movements or small wrist movements may have introduced errors. The sources and relative contributions to the errors cannot be determined in this study.

5.3 Feasibility of thumb electrogoniometry – Study III

The study identified the joint ranges of motion used when operating mobile phones. When subjects used their own phone, maximal flexion (5th percentile position) was -23.2º which represented 55% (-23.2º/-42.3º) of the maximal voluntary flexion and maximal extension (95th percentile position, actually still thumb flexion) was -6.4º flexion (Tables 10 and 11). With regard to thumb Ad/Ab, maximal adduction (5th percentile position) was -6.3º and maximal abduction (95th percentile position) was 26.2º, which represented 79% (26.2º/33.0˚) of the thumb’s maximal voluntary abduction. When using the standard phone, the abduction was as high as 98% (32.5º/33º) of maximal voluntary abduction, likely due to the greater width of the standard phone. This demonstrates that operating at near extremes in abduction and sustained thumb flexion are possible postural risk factors that may be contributing to mobile phone-based thumb disorders. In addition, movement velocities have also been shown to be risk factors that may lead to injury. Based on movement velocities, Ad/Ab movements were at twice the speed of Flex/Ext movements and Ad/Ab movement may pose a greater risk than Flex/ Ext movements for thumb-related injuries.

Finally, the electrogoniometers performed well in measuring differences in thumb movements and postures between mobile phones. Small systematic postural differences between phones were measured, which appear to be related to differences in mobile phone dimensions. The subjects’ own mobile phones were on average thinner and narrower than the standard mobile phone. The expectation in relation to posture would be that there would be more thumb flexion when the subjects operated their own mobile phones and less abduction and a narrower range of Ad/Ab due to the fact that their own mobile phones were on average thinner and narrower than the standard phone. As indicated in table 11, this was for the most part the case.

In addition, the high posture correlations between phones indicated that the individual's working technique with their own phone carried over and was used on the standard phone. This indicated that the standard phone systematically altered posture to a small degree but did not overly influence working technique. This has implications for future mobile phone-based studies, indicating that an individual's working technique may be captured when using a standard mobile phone.

During mobile phone handling there may have been some error/bias associated with the position of the wrist, but overall the wrist was relatively motionless during the mobile phone use so registration of velocity and MPF of the two thumb joints should have been minimally affected.

5.4 Thumb electrogoniometry and EMG associations – Study IV

In this controlled laboratory study, associations between thumb-based exposures simultaneously registered with electrogoniometers and EMG were investigated during mobile phone texting. Significant group correlations were found when exposure parameter combinations, averaged over the full duration of the texting task, were compared. In addition, correlations were seen in a few of the cross-correlations calculated between the two signals. These two different types of correlations were not strongly associated to one another, i.e. exposure combinations showing strong group correlation were often weakly cross-correlated. This indicates that the group level correlations between EMG and goniometer may have a lower temporal association and may be less directly related to one another than the associations identified by the cross correlations. Since goniometry measures an external exposure - the angle, while EMG measures an internal exposure - the force, electrogoniometry and EMG give various aspects of exposure and do not generally substitute each other.

5.4.1 GROUP CORRELATIONS

Surprisingly, few correlations were found between thumb movements and thumb muscle (APL and APB) activity (Table 12). Nevertheless, subjects with higher adduction/abduction velocities showed increased APB activity. Strong correlations between wrist flexion/extension velocity and extensor carpi radialis muscular load have been reported by (Hansson et al., 2008) but the correlations between the measures of muscular activity and wrist positions were in general weak.

The function of APL muscle is to extend (radially abduct) and assist reposition (reverse of opposition) of the TMC- joint (Jenkins and Hollinshead, 2009). Study III showed very little extension during mobile phone texting explaining the lack of associations with APL activity. Subjects with a more adducted thumb tended to show higher peak APL loads, other studies have shown the APL has a stabilising function on the wrist and basal joint of the thumb (van Oudenaarde, 1991); (van Oudenaarde et al., 1995).

ED and FDI muscle activity were often associated with thumb postures and movement (Table 12). These muscles are not directly predisposed for thumb movements but seem to be involved in the stabilization and relaxation of the hand during mobile phone texting. Subjects who were more prone to work in adduction and who had higher adduction/abduction velocities showed a clearly higher ED activity, indicating wrist stabilization. Furthermore, subjects more prone to work in thumb flexion showed lower load and more rest in the FDI muscle promoting more relaxation in that muscle whereas for subjects with less flexion to a more neutral position the stabilizing role of the FDI muscle was more pronounced.

5.4.2 CROSS CORRELATIONS

For APB, strong cross-correlations both for adduction/abduction angle and velocity were found indicating associations between exposure registered with electrogoniometers and EMG (Table 13). This association could be expected since this muscle's function is to help abduct the thumb. All subjects had cross-correlations over 0.3 between abduction angle and APB muscle activity with, on average, the postures following the muscle activity by 0.13 s (Table 14). However, there was almost no delay between the movement velocity signal and the APB muscle activity. This was expected since the posture is the integral of velocity and a peak in posture comes after a peak in velocity. In a typical recording, it was visually obvious how APB activity resulted in an immediate change in abduction velocity, muscle contraction acts in one direction and the muscle is relatively passive in the other direction (Figure 14).

Very low correlations between thumb movements and the activity of the APL were seen, this muscle seems not to be dynamically involved during mobile phone texting.

Only very low cross-correlations between thumb movements and the activity of the FDI were seen, this muscle is not directly involved in thumb movements but acts on and can stabilize the index finger (Jenkins and Hollinshead, 2009) (Putz et al., 2006).

For the ED only one moderate cross-correlation was seen, peaks in the EMG usually appeared together in time with peaks in the abduction angle and rarely with adduction angles (Table 13). This finding is somewhat puzzling since the ED is hardly a muscle that contributes in thumb abduction, it seems however to stabilize the wrist during peaks in abduction.

5.4.3 COMPARISON OF GROUP AND CROSS CORRELATION

The group correlation method compares parameters computed over the whole time period and exploits the range of these data across the group of subjects while the cross correlation method compares the dynamic time varying signals and exploits the temporal agreement for each subject. Group correlations were seen for ED and ad/ab postures as well as for velocities but this was not consistent with the cross correlation. The ED may stabilize wrist during fast thumb movements but, as reflected by the low cross correlation seen for velocity, it does not precede thumb movements in time since ED is not a thumb activating muscle.

Considering the two correlation methods only APB activity and thumb angle velocity showed good consistency, and a direct correlation since both methods showed positive correlations between muscle activity and adduction/abduction velocity. This was to be expected since APB is a thumb abductor (Jenkins and Hollinshead, 2009); (Putz et al., 2006).

5.4.4 STATISTICAL SIGNIFICANCE

In this study numerous correlations were computed. Here correlations above 0.6 for group correlations and 0.2 for cross-correlations were chosen for presentation. Values fulfilling the criteria represented statistically significant correlations of the two types. The reason for the lower criterion was that this type is likely to be much smaller. This is due to the large variation *in each of the EMG ARV samples*. The EMG raw signal is a random signal and 50-ms ARV values by nature have a large variation (this is true even for an isometric contraction at a static force level). On the other hand, each value of the cross correlations is a sum of a high number of products, why they become significant also for lower correlation levels.

5.5 Limitations, methodological considerations

5.5.1 WRIST ELECTROGONIOMETRY – STUDY I & II

One limitation was that the goniometers were not tested over the full range of wrist movements, as a result, possible measurement errors associated with extreme postures were not characterised or identified. A second limitation was that measurement errors associated with dynamic wrist movements were not characterised; velocity, acceleration and repetitiveness (e.g. MPF, mean power frequency) measures could also be affected (Van Vorhis, 1996). Finally, a third limitation is the limited accuracy associated with our methods used to position the wrist and forearm and any biases that may be associated with the use of our wrist positioning apparatus. Other methods to position the wrist may be more or less accurate and our apparatus used to control wrist postures may also affect measurement and the comparability/compatibility of results to other previous or future studies.

System A is readily available whereas System B presently is not. Most work in goniometry has been performed with System A. Based on our results, with respect to crosstalk, it appears that the transducer placement for System A can be optimised for one pronation/supination position, but not a range of P/S positions.

Goniometer crosstalk has been identified by others as an important and substantial source of measurement error (Hansson et al., 1996), (Buchholz and Wellman, 1997) and it has been postulated that crosstalk could be a result of twisting the goniometer. Our results confirm this finding and demonstrate that the crosstalk can be substantially reduced with a goniometer design that does not impart twist to the transducer during normal wrist and forearm movements.

A fair amount of work has been put into developing mathematical algorithms to correct for the errors in the goniometer signal with System A (Hansson et al., 1996), (Buchholz and Wellman, 1997), (Hansson et al., 2004). System B demonstrated that the need for some mathematical corrections could be eliminated through enhancements in goniometer design.

Other important aspects to consider is the fact that slight, almost undetectable movements during calibration can substantially affect the offsets of System A and B. The definition of the “zero/reference” position is critical for comparisons between studies. We used the positions recommended by American Academy of Orthopaedic Surgeons (Greene et al., 1994). For F/E, the neutral (reference) position was defined by the position when the plane of the back of the hand was in line with the plane on the dorsal surface of the forearm. If the F/E reference position was defined as the posture assumed when the forearm was resting flat on the work surface and the hand pressed flat, anecdotally it was observed typically at least a 7° difference between the two reference positions. In addition, our experience from positioning the wrist in the calibration fixture was that it was hard to visually repeat postures better than ± 4° and the subtle difference between having the fingers relaxed (slightly curled) versus the fingers flat in the calibration fixture can affect the F/E wrist angle by as much as 10°. Furthermore, the glove (system B), accidently can change position on the hand after calibration because it’s not firmly taped (as system A), which then gives an ”offset error”.

5.5.2 THUMB ELECTROGONIOMETRY – STUDY III & IV

5.5.2.1 The combined angle of three joints

The main presumption was to use common and easy-to-use equipment, which also can be used outside the lab, for determining thumb exposure. No biaxial goniometer is available that exclusively measures thumb movements. A long type of goniometer to measure the relative angle between thumb's proximal phalanx and the radius bone was used. This goniometer, as attached to the subjects, measured the combined angle of three joints: the wrist joint (scaphoradial); the TMC joint; and the MCP joint. Thumb movements involving angle changes in opposite directions in these joints may give underestimated readings and even cancel out an existing change in posture. Conversely, when some of these joints move with the thumb in the same direction, there may be an overestimation of the thumb movements. In the measurements of the reference and maximal postures, the wrist was restrained in a neutral position, resulting in pure TMC joint and MCP joint measurements. During mobile phone handling there may have been some error/bias associated with the position of the wrist but, overall, the wrist was relatively motionless since the subjects wrists appeared virtually locked in one position when they entered text messages, so registration of velocity and MPF of the two thumb joints should have been minimally affected.

5.5.2.2 Crosstalk

The electrogoniometer used in the study were prone to crosstalk (i.e. when movement in one plane (e.g. Flex/Ext) causes a false signal in the other plane (e.g. Ad/Ab)) due to twisting of the goniometer's transducers (Hansson et al., 1996), (Buchholz and Wellman, 1997). This was not controlled for in the present study and may be a source of error, when measuring thumb movements, since the goniometer transducers may be subject to twisting over the range of thumb movements.

There are more exact methods of assessing thumb position. (Tang et al., 2008) used cameras and optical markers on the separate joints, but their method represents a higher degree of complexity.

5.5.2.3 The phone size.

The size (113 mm x 22 mm x 48 mm) of the standard mobile phone used obviously had an influence on thumb posture relative to the subjects' own phone which tended to be smaller, but the size of the standard phone was quite typical relative to the other models commercially available. However, there are a wide range of models of cell phones on the market today, some smaller and some larger than the phone tested in our study.

5.5.2.4 The hand size

Effects due to different hand size (differences were actually small in the studied group) or different gripping techniques depending on phone shape has not been investigated here.

5.5.2.5 The text message task

The subjects finished the 300 character texting task in between 124 s and 374 s, a considerable difference in writing speed, which might influence angular velocity, and muscular activity as well, but no test for any of our exposure parameters and their relation to texting speed was done.

The correlation between movement pauses and muscular rest periods was investigated, both important factors when dealing with musculoskeletal disorders. This mobile phone texting task is not ideal for investigation of pauses and rest periods since the subjects were expected to be continuously active; low values and very low correlations were seen.

5.5.3 EMG – STUDY IV

The surface EMG registration was chosen on four superficial muscles with distinct muscle bellies which facilitated their localization. The selected muscles were also far apart from one another which should have minimized the potential for EMG cross-talk between the selected muscles. These muscles are also known to be involved in a gripping task. The ED muscle is also commonly investigated in ICT input device studies. Deeper thumb muscles, which could be measured using needle or wire electrodes, may have more promise for measuring thumb-related exposures, but these methods of electromyography is invasive, requires a skilled technician and verifying correct electrode placement can be challenging.

The measurement error for the normalized EMG was not investigated but the noise level in a resting posture was low, typical below 3 μV corresponding to 0,6 % MVE. The measurement errors or noise were considered to have a low influence on the degree of correlation between EMG and electrogoniometry.

Cross-talk between the EMG signals from the neighbouring muscles has been reported (Mogk and Keir, 2003), but the distance between the electrodes of the four investigated muscles and the choice of dominant bellies are likely adequate to make this phenomenon negligible.

6 CONCLUSIONS

This thesis may be helpful for designing new studies or to interpret resent studies concerning wrist and thumb joint postures and motions. Today's available electrogoniometer systems are fairly easy to use and give appropriate exposure data. But electrogoniometry does have limitations and it is important that those who prepare and perform measurements with electrogoniometers understands those limitations. For instance, the procedure of calibrating and normalizing the electrogoniometer is of crucial importance and will affect measurement accuracy. Certain methodological as well as physical changes to the electrogoniometers themselves could improve measurement accuracy. Electrogoniometry and EMG give various aspects of exposure and do not generally substitute each other.

6.1 Wrist goniometry accuracy – Study I & II

The overall conclusions from the wrist joint studies can be summarised as follows:

Two goniometer systems with different designs showed important deviations from the “Gold Standard” positions the wrist was placed in. Evaluation of wrist posture can be facilitated by using either of the goniometer systems but knowing the limitations of each system will be important in the context of collecting and interpreting results.

Goniometer transducers employing a twist reducing design can substantially reduce crosstalk.

For goniometers without twist reducing designs, placing the wrist and forearm in known positions and using a software-based error correcting algorithm could be employed to reduce crosstalk.

Crosstalk errors are dependent on how the goniometers reside on the wrist relative to the joint centres of rotation. Goniometer placement relative to the wrist joint centres is important and will influence the direction and magnitude crosstalk.

To minimize offset errors, goniometers should be calibrated/zeroed in the most common P/S position or in the mid-range of anticipated P/S positions

Standardization in the use of goniometers would facilitate comparisons within and between studies when different methods or equipments are used. For example, how neutral wrist positions are defined and the pronation/supination positions chosen to calibrate/zero the goniometers are important considerations when comparing results.

6.2 Thumb goniometry accuracy – Study III

This study demonstrated that a commonly used, relatively uncomplicated electrogoniometer can measure thumb positions.

Typically thumb postures were measured with no more than ±5° degrees of error which should be sufficient for clinical purposes

Crosstalk between the movement axes might be present due to twisting of goniometers, but was not investigated.

6.3 Feasibility of thumb electrogoniometry – Study III

Electrogoniometers can provide quantitative information on thumb movements during thumb-intensive task such as mobile phone use and may be useful for studying other thumb-based activities.

It was possible to measure differences in the speed of thumb movements - thumb movements were twice the speed in adduction/abduction compared to flexion/extension during SMS texting.

It was possible to measure small differences in thumb positions – relative to the subjects' own phones which were smaller, there was larger thumb abduction with the standard mobile phone, probably related to larger size of the standard phone.

It was possible to investigate to what extent the thumb's range of motion was used – with the subject's own phone, 79% of max-abduction ability was used but as much as 98% with the standard mobile phone.

Thumb movement goniometry may include wrist movements but separation on different joints is not possible in the method described.

6.4 Thumb electrogoniometry and EMG associations – Study IV

The levels of the two correlations, group and cross, were generally not sufficiently high for a recommendation of substituting EMG with electrogoniometry or vice versa for measuring thumb exposure during mobile phone text messaging.

For one goniometric and EMG combination, the abduction velocity and APB activity, both the group and the cross correlation methods demonstrated high correlations. For this specific exposure, EMG and electrogoniometry may substitute each other.

APL muscle showed low correlation to thumb movements; this muscle seems not to be dynamically involved during mobile phone texting.

ED showed a high muscular activity while stabilizing the wrist during thumb motion.

EMG on the specific thumb muscles (there are four in the wrist and four in the hand) may be a better measure of reflecting specific thumb exposure than the electrogoniometric method described.

7 SUGGESTIONS FOR FUTURE WORK

7.1 Wrist goniometry – Study I & II

Offset errors were present with both systems and depended on the P/S position. If a device was developed that accurately measured P/S position, these measurements could be used to correct the offset errors. One way to do so would be to build a transducer that is both a goniometer and a torsiometer. In that way, in conjunction with a calibration routine (putting the forearm in various P/S positions), the torsiometer signal could be used as input to correct offset errors in the goniometer signal.

7.2 Thumb goniometry – Study III

Subtraction of wrist movements from the thumb mounted goniometer would be possible if a separate wrist electrogoniometer was used. In this configuration, the wrist movements superimposed on the thumb signals could be subtracted using the signal from the wrist-mounted electrogoniometer. Alternative goniometer designs such as a segmented electrogoniometer which measures the thumb IP and MCP joints independently would be another way of addressing some of the limitations.

7.3 Thumb electrogoniometry and EMG associations – Study IV

Except the two muscles, APB and APL, measured in this study there are totally eight specific thumb muscles, four extrinsic in the forearm and four intrinsic in the hand. EMG on other specific thumb muscles may be a better measure of reflecting specific thumb exposure. Deeper muscles, which could be measured using invasive needle or wire electrodes, may have more promise for measuring thumb-related exposures.

Summary

Correct measurements of the joints' extreme postures, velocity and repetitiveness are important for studies of the origin of musculoskeletal disorders. Posture measurements of wrist and thumb joints may also provide insights into input device designs that may reduce effort and/or facilitate productivity. Electrogoniometry offers a relatively simple and objective way to measure joint postures and motions. The expectation is that electrogoniometric instruments will provide better measures of postures and movements than the more subjective methods such as self-reporting or observation.

In the first part of this thesis, two wrist goniometer systems were evaluated. The systems differed in how the goniometers were engineered and positioned over wrist and forearm. One system was integrated into a fingerless glove and floated over the forearm whereas the other system was mounted directly over the wrist. ”True” wrist positions were established with the aid of a fixture that allowed the positioning of the wrist in known angles. The “Crosstalk” – when movement in one plane artificially causes movement to be measured in another movement plane, “offset” – where the measured movement axes differ or are offset from the actual movement axes, and “range of motion” – the difference between the actual and measured range of motion of the joint, were compared. The measurement errors were substantial with both systems for simple, standardized wrist postures. However, the system with the transducers built-in in the fingerless glove had considerably less crosstalk errors and proved to have less between-subject differences. The similarities and differences in the measurement errors could be attributed to differences in systems design and methods to improve the accuracy of wrist posture measurement were provided.

In the second part of this thesis, the accuracy and feasibility of measuring thumb postures and movements with a simple thumb-mounted electrogoniometer were evaluated. The ”true” thumb positions were established and defined using a manual goniometer. The posture measurement error of the thumb-based electrogoniometer was small relative to the manual goniometer, and on average, less than 5 degrees. A follow-up study determined whether this simple thumb-mounted goniometer could provide meaningful information on thumb posture during mobile phone use. When measuring thumb posture during SMS messaging, thumb posture was shown to be affected by the size of the mobile phone and differences in movement speeds were seen between the two movement axes of the thumb. Thumb movements in abduction/adduction were almost twice as fast as those in flexion/extension. It was also established that the thumb worked near the extreme ranges of motion – which is known to contribute to musculoskeletal disorders.

Finally, this thesis determined whether measurements with a simple, thumb mounted electrogoniometer could be used in place of more complicated measures of muscle activity (EMG) for assessing musculoskeletal load during mobile phone use. Sophisticated correlation analyses of these different methods showed that only during very limited conditions could thumb goniometry be used in lieu of EMG measurements to assess musculoskeletal loads. Measurements indicated that the thumb's muscle activity most often complemented rather than replaced the simple goniometric measures of the thumb.

Sammanfattning
(Summary in Swedish)

Handledens och tummens ställning och rörelse - mätningar med elektrogoniometri och EMG

Korrekta mätningar av ledernas ytterlighetslägen, rörelsehastighet och repetitivitet är viktiga vid studier av uppkomsten av muskuloskeletala besvär. Korrekta mätningar av handleds- och tum-rörelser kan också bidra till utformning av inmatningsdon som ger minskad ansträngning och som underlättar arbetet. Elektrogoniometri erbjuder en relativt enkel och objektiv metod att mäta ledrörelser. Förhoppningen är att sådana mätningar skall ge ett bättre mått än mer subjektiva metoder som självrapportering eller observation.

I den första delen av avhandlingen undersöktes två elektrogoniometrar som skiljde sig i konstruktion och placering på handleden. Det ena systemet hade dubbla vinkelgivare inbyggda i en fingerlös handske medan det andra fästs med specialtejp över handleden. Den ”sanna” handledsställningen fastställdes med hjälp av en fixtur för inställning av handledsvinkeln i kända positioner.”Crosstalk” – en felaktig överhörning mellan de uppmätta rörelseplanen, ”offset” – rörelseaxlarnas förskjutning från det rätta läget och ”range of motion” – skillnaden mellan ”sant” och uppmätt rörelseomfång, jämfördes. Mätfelen visade sig vara betydande för båda systemen även vid relativt enkla standardiserade handledsställningar. Systemet med givarna inbyggda i handsken hade dock betydligt mindre ”crosstalk” och uppvisade mindre spridning mellan testpersonerna. Likheter och olikheter i mätfelen kunde relateras till skillnader hos systemens utformning och förslag ges på förbättrade metoder för mätning av handledsvinklar.

I den andra delen av avhandlingen undersöktes mätfelet och funktionsdugligheten hos en enkel elektrogoniometer som fästes på tummen. Den ”sanna” tum-positionen fastställdes genom manuell vinkelmätning med gradskiva. Mätfelet visade sig vara litet, i genomsnitt mindre än 5 grader.

Vidare undersöktes huruvida den enkla elektrogoniometern fäst på tummen kunde ge användbar exponeringsinformation under mobiltelefon-användning. När försökspersonerna skrev SMS-meddelanden kunde uppmätta skillnader i tummens ställning relateras till storleken på mobiltelefonen. Dessutom kunde skillnader i hastigheter mellan tummens olika rörelseriktningar upptäckas; rörelser i abduktion/adduktion var dubbelt så snabba som i flexion/extension. Det konstaterades också att tummen arbetade nära ytterläget för sitt rörelseomfång, något som påverkar uppkomsten av besvär.

Slutligen undersöktes huruvida mätning med den enkla elektrogoniometern fäst på tummen kan ersätta en mer komplicerad mätning av elektrisk muskelaktivitet (EMG) vad gäller bedömning av belastningen under mobiltelefon-användning. Avancerad korrelationsanalys av dessa olika elektriska mätmetoder visade att elektrogoniometri istället för EMG för belastningsbedömning var möjligt bara under mycket begränsade betingelser. Mätning av tummens rörelser och mätning av tummens muskelaktivitet visar oftast olika aspekter av belastningen och mätmetoderna kompletterar snarare än ersätter varandra.

Acknowledgements

I would particularly like to thank my supervisors Mats Hagberg, Pete Johnson and Mikael Forsman as well as my colleagues Ewa Gustafsson, Gunnar Palmerud and Leif Sandsjö for valuable support.

Financial support was given by the Swedish Council for Working Life and Social Research.

References

ALTMAN, D. G. (1991) *Practical statistics for medical research,* London, Chapman and Hall.

BASMAJIAN, J. V. & DE LUCA, C. J. (1985) *Muscles alive : their functions revealed by electromyography,* Baltimore, Williams & Wilkins.

BENDAT, J. S. & PIERSOL, A. G. (2000) *Random data : analysis and measurement procedures,* New York, Wiley.

BUCHHOLZ, B. & WELLMAN, H. (1997) Practical operation of a biaxial goniometer at the wrist joint. *Hum Factors,* 39**,** 119-29.

CHIU, H. Y., SU, F. C., WANG, S. T. & HSU, H. Y. (1998) The motion analysis system and goniometry of the finger joints. *J Hand Surg [Br],* 23**,** 788-91.

EDWARDS, G. L., ROTHENBERG, S. J. & OBERMAN, M. L. (1996) Electronically aligned man-machine interface. *United States Patent* United States.

FONTANA, L., NEEL, S., CLAISE, J. M., UGHETTO, S. & CATILINA, P. (2007) Osteoarthritis of the thumb carpometacarpal joint in women and occupational risk factors: a case-control study. *J Hand Surg [Am],* 32**,** 459-65.

FREDRIKSSON, K. (1995) Laboratory work with automatic pipettes: a study on how pipetting affects the thumb. *Ergonomics,* 38**,** 1067-73.

GREENE, W. B., HECKMAN, J. D. & AMERICAN ACADEMY OF ORTHOPAEDIC SURGEONS (1994) *The clinical measurement of joint motion,* Rosemont, Ill., American Academy of Orthopaedic Surgeons.

GUSTAFSSON, E. (2009) *Physical exposure, musculoskeletal symptoms and attitudes related to ICT use,* Göteborg, Institute of Medicine at Sahlgrenska Academy, University of Gothenburg.

GUSTAFSSON, E. & HAGBERG, M. (2003) Computer mouse use in two different hand positions: exposure, comfort, exertion and productivity. *Appl Ergon,* 34**,** 107-13.

GUSTAFSSON, E., JOHNSON, P. W. & HAGBERG, M. (2009) Thumb postures and physical loads during mobile phone use - A comparison of young adults with and without musculoskeletal symptoms. *J Electromyogr Kinesiol.*

HAGBERG, M. (1979) The amplitude distribution of surface EMG in static and intermittent static muscular performance. *Eur J Appl Physiol Occup Physiol,* 40**,** 265-72.

HAGBERG, M., FORCIER, L. & KUORINKA, I. (1995) *Work related musculoskeletal disorders (WMSDs) : a reference book for prevention,* London, Taylor & Francis.

HANSSON, G.-A., BALOGH, I., OHLSSON, K., RYLANDER, L. & SKERFVING, S. (1996) Goniometer measurement and computer analysis of wrist angles and movements applied to occupational repetitive work. *Journal of Electromyography and Kinesiology,* **6,** 23-35.

HANSSON, G.-A. & MIKKELSEN, S. (1997) Kinematic evaluation of occupational work. *Advances in Occupational Medicine and Rehabilitation,* **3,** 57-69.

HANSSON, G.-Å., BALOGH, I., OHLSSON, K., GRANQVIST, L., NORDANDER, C., ARVIDSSON, I., ÅKESSON, I., UNGE, J., RITTNER, R., STRÖMBERG, U. & SKERFVING, S. (2008) Physical workload in various types of work: Part I. Wrist and forearm. *International Journal of Industrial Ergonomics,* In Press, Corrected Proof.

HANSSON, G. A., ASTERLAND, P. & KELLERMAN, M. (2003) Modular data logger system for physical workload measurements. *Ergonomics,* **46,** 407-15.

HANSSON, G. A., BALOGH, I., OHLSSON, K. & SKERFVING, S. (2004) Measurements of wrist and forearm positions and movements: effect of, and compensation for, goniometer crosstalk. *J Electromyogr Kinesiol,* **14,** 355-67.

HOLLISTER, A., BUFORD, W. L., MYERS, L. M., GIURINTANO, D. J. & NOVICK, A. (1992) The axes of rotation of the thumb carpometacarpal joint. *J Orthop Res,* **10,** 454-60.

HÄGG, G. M. (2001) *Handintensivt arbete - En belastningsergonomisk kunskapsöversikt gällande människans kapacitet och interaktion med verktyg och arbetsuppgifter,* Stockholm, Arbetslivsinstitutet.

HÄGG, G. M., OSTER, J. & BYSTROM, S. (1997) Forearm muscular load and wrist angle among automobile assembly line workers in relation to symptoms. *Appl Ergon,* **28,** 41-7.

JENKINS, D. B. & HOLLINSHEAD, W. H. (2009) *Hollinshead's functional anatomy of the limbs and back,* St. Louis, Saunders Elsevier.

KAZMIERCZAK, K., MATHIASSEN, S. E., FORSMAN, M. & WINKEL, J. (2005) An integrated analysis of ergonomics and time consumption in Swedish 'craft-type' car disassembly. *Appl Ergon,* **36,** 263-73.

KINOSHITA, H., MURASE, T. & BANDOU, T. (1996) Grip posture and forces during holding cylindrical objects with circular grips. *Ergonomics,* **39,** 1163-76.

KUO, L. C., COONEY, W. P., 3RD, OYAMA, M., KAUFMAN, K. R., SU, F. C. & AN, K. N. (2003) Feasibility of using surface markers for assessing motion of the thumb trapeziometacarpal joint. *Clin Biomech (Bristol, Avon),* **18,** 558-63.

KUO, L. C., SU, F. C., CHIU, H. Y. & YU, C. Y. (2002) Feasibility of using a video-based motion analysis system for measuring thumb kinematics. *J Biomech,* **35,** 1499-506.

LINDEGARD, A., WAHLSTROM, J., HAGBERG, M., HANSSON, G. A., JONSSON, P. & WIGAEUS TORNQVIST, E. (2003) The impact of working technique on physical loads - an exposure profile among newspaper editors. *Ergonomics,* **46,** 598-615.

MARRAS, W. S. & SCHOENMARKLIN, R. W. (1993) Wrist motions in industry. *Ergonomics,* 36**,** 341-51.

MATHIASSEN, S., WINKEL, J., HÄGG, G. (1995) Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies - a review. *J Electromyogr Kinesiol,* 5**,** 197-226.

MERLETTI, R., PARKER, P. & KNOVEL (FIRM) (2004) *Electromyography : physiology, engineering, and noninvasive applications,* Piscataway, NJ; Hoboken, N.J., IEEE Press ; Wiley-Interscience.

MING, Z., PIETIKAINEN, S. & HANNINEN, O. (2006) Excessive texting in pathophysiology of first carpometacarpal joint arthritis. *Pathophysiology,* 13**,** 269-70.

MOGK, J. P. & KEIR, P. J. (2003) Crosstalk in surface electromyography of the proximal forearm during gripping tasks. *J Electromyogr Kinesiol,* 13**,** 63-71.

MOORE, J. A., SMALL, C. F., BRYANT, J. T., ELLIS, R. E., PICHORA, D. R. & HOLLISTER, A. M. (1993) A kinematic technique for describing wrist joint motion: analysis of configuration space plots. *Proc Inst Mech Eng H,* 207**,** 211-8.

MOORE, J. S. (1997) De Quervain's tenosynovitis. Stenosing tenosynovitis of the first dorsal compartment. *J Occup Environ Med,* 39**,** 990-1002.

MORK, P. J. & WESTGAARD, R. H. (2007) The influence of body posture, arm movement, and work stress on trapezius activity during computer work. *Eur J Appl Physiol,* 101**,** 445-56.

PEROTTO, A. & DELAGI, E. F. (1994) *Anatomical guide for the electromyographer : the limbs and trunk,* Springfield, Ill., USA, Charles C. Thomas.

PUTZ, R., PABST, R., BEDOUI, S. & SOBOTTA, J. (2006) *Sobotta atlas of human anatomy. Vol. 1, Head, Neck, Upper Limb,* München, Elsevier Urban & Fischer.

RADWIN, R. G. & LIN, M. L. (1993) An analytical method for characterizing repetitive motion and postural stress using spectral analysis. *Ergonomics,* 36**,** 379-89.

TANG, J., ZHANG, X. & LI, Z. M. (2008) Operational and maximal workspace of the thumb. *Ergonomics,* 51**,** 1109-18.

THOMÉE, S., EKLÖF, M., GUSTAFSSON, E., NILSSON, R. & HAGBERG, M. (2007) Prevalence of perceived stress, symptoms of depression and sleep disturbances in relation to information and communication technology (ICT) use among young adults - an explorative prospective study. *Computers in Human Behavior,* 23**,** 1300-1321.

THORN, S., SOGAARD, K., KALLENBERG, L. A., SANDSJO, L., SJOGAARD, G., HERMENS, H. J., KADEFORS, R. & FORSMAN, M. (2007) Trapezius muscle rest time during standardised computer work--a comparison of female computer users with and without self-reported neck/shoulder complaints. *J Electromyogr Kinesiol,* 17**,** 420-7.

WAHLSTRÖM, J., HAGBERG, M., JOHNSON, P. W., SVENSSON, J. & REMPEL, D. (2002) Influence of time pressure and verbal provocation on physiological and psychological reactions during work with a computer mouse. *Eur J Appl Physiol,* 87**,** 257-63.

WAHLSTRÖM, J., HAGBERG, M., TOOMINGAS, A. & WIGAEUS TORNQVIST, E. (2004) Perceived muscular tension, job strain, physical exposure, and associations with neck pain among VDU users; a prospective cohort study. *Occup Environ Med,* 61**,** 523-8.

WAHLSTRÖM, J., LINDEGARD, A., AHLBORG, G., JR., EKMAN, A. & HAGBERG, M. (2003) Perceived muscular tension, emotional stress, psychological demands and physical load during VDU work. *Int Arch Occup Environ Health,* 76**,** 584-90.

WAHLSTRÖM, J., SVENSSON, J., HAGBERG, M. & JOHNSON, P. W. (2000) Differences between work methods and gender in computer mouse use. *Scand J Work Environ Health,* 26**,** 390-7.

VAN OUDENAARDE, E. (1991) The function of the abductor pollicis longus muscle as a joint stabiliser. *J Hand Surg [Br],* 16**,** 420-3.

VAN OUDENAARDE, E., ELVERS, J. W. H., GIELEN, C. C. A. M., KAUER, J. M. G., OOSTENDORP, R. A. B. & VAN DER STRAATEN, J. H. M. (1995) Differences and similarities in electrical muscle activity for the abductor pollicis longus muscle divisions. *Journal of Electromyography and Kinesiology,* 5**,** 57-64.

VAN VORHIS, R. (1996) Kinematic measurements about wrist functional anatomic axis - Validation of mechanical wrist phantom for ergonomic motion studies. *Risk Assessment for Musculoskeletal Disorders. Nordic Satellite Symposium under the auspices of ICOH '96.* Denmark, National Institute of occupational Health.

WESTGAARD, R. H., VASSELJEN, O. & HOLTE, K. A. (2001) Trapezius muscle activity as a risk indicator for shoulder and neck pain in female service workers with low biomechanical exposure. *Ergonomics,* 44**,** 339-53.

YOUM, Y. & YOON, Y. S. (1979) Analytical development in investigation of wrist kinematics. *J Biomech,* 12**,** 613-21.