JOINT KINEMATICS, MUSCLE ACTIVITY AND POSTURAL STRAIN FOR FINGER-INTENSIVE OPERATION OF SMALL HAND- HELD DEVICES

by

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To

Abbu and Ammu

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Abstract

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Background: Extensive movement of fingers while playing video games, and while browsing or texting in a smartphone often result in medically recognized repetitive strain injuries such as “PlayStation thumb” or “Blackberry thumb”. In order to understand the strenuous effects of these tasks, it is important to study the geometry of the movement of fingers (kinematics), corresponding muscle activities (physiology), and the overall posture of the tasks (ergonomics). There is almost no information available in the present literature regarding the finger kinematics of video gaming. Although texting and browsing tasks have been studied, a multifaceted approach including kinematic, physiological and postural information together is not present. In intricate finger-intensive tasks, how the ergonomic posture analysis variables relate to kinematic and physiological variables, is also not known. *Methods:* Three tasks: playing a videogame (using a sequential and a natural protocol), texting in a smartphone (using index finger of dominant hand, or thumb of dominant hand) and browsing in a smartphone (using index finger of dominant hand, or thumb of dominant hand) were performed by ten subjects in a laboratory setting. Joint angles, velocities and accelerations of the metacarpophalangeal (MCP) and the interphalangeal (IP) joints of the index finger and thumb were calculated. At the same time, the electromyography (EMG) signals were collected from the first dorsal interossei (FDI) and the extensor digitorum (ED) muscles; and later, ergonomic postural risk analyses were conducted using Hand Activity Level (HAL) and Rapid Upper Limb Assessment (RULA) tools. Thus, a total of 49 measures of strain were obtained. *Findings:* . Video gaming and texting activities resulted in very high velocities and accelerations at the interphalangeal joints of both the fingers; and extremely high repetitive movements (more than 110,000 reps/day). Browsing activities showed very rapid motion at the metacarpophalangeal joint of the thumb. Muscular activity was higher at the ED muscle for all the tasks. Ergonomic task analysis variables, on the average, correlated significantly with 26% of the other variables. *Interpretations:* The information acquired through this study is novel, and we provided suggestions for better design of game controllers. Very high risk of overuse injuries and damage of the articular cartilage was established. We also provided suggestions regarding better posture for single-fingered texting and browsing activities on smartphones. Finally, from our results, we concluded that observational ratings of postural strain may not be suitable substitutes for kinematic or EMG measures.

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Chapter 1

Introduction

The use of personal data devices has grown more and more popular over the last few decades. In recent years, phenomenal technological advancements have taken place in the areas of mobile phone design, network, operating system, internet connectivity and entertainment activities. In addition to personal computers, we now use sophisticated entertainment and data processing devices of various sizes and shapes that fit into our palms. Mobile phones, tablets, laptops, gaming consoles, e-book readers, etc. are some examples of small hand held devices that have made our lives easier, more enjoyable and more interconnected. However, operating most of these devices require very frequent or repetitive micro-movements of our fingers that may lead to muscular fatigue and cumulative trauma disorders in the hand. Knowing the pattern of these movements can give us scientific information about sources of these problems, and, perhaps, methods for controlling and eliminating them.

In the current study, we will determine and analyze the kinematics of fingers while using two types of small hand held devices: video game controller and smartphone; using biomechanical and ergonomic techniques.

1.1 Finger Intensive Media Tasks and Finger Motions

Human hands are wonderful tools that can perform multidirectional activities involving varying forces. Our fingers are the most active parts of this tool. Fingers are used to exert forces in different directions so that a particular task objective can be attained. Whether we grasp, pinch, push, pull, hold, poke or simply touch something, we are using our fingers, and in some cases, the palm also, to apply or impart forces on an object.

Over the past few decades, researchers have been concerned with occupational injuries involving repetitive motion of the hands and fingers (Tichauer, 1966, Armstrong and Chaffin, 1978 etc.). Industrial work, such as hammering, sawing, using screw drivers, assembling parts, typing etc. have been reported to be associated with inflammation and injuries of the hand, especially the wrist. These injuries, such as tenosynovitis or tendinitis, have been associated with certain patterns of movement of the hands and fingers (Tichauer, 1966, Armstrong and Chaffin, 1978). Also, researchers are certain that although hand intensive activities may not pose any immediate danger of injury, over many years of activity, effects will accumulate, resulting in cumulative trauma (Chaffin et al., 1999).

While industrial and occupational hand intensive tasks have been rigorously studied for many years, there are other tasks outside the industrial arena that require attention. Recent boom in smart technology has resulted in our usage of smart devices and other media devices almost throughout the day, every day. We call these tasks “finger intensive media tasks” since the operation of most small hand held media device involves very fast movement of the fingers while the wrist is generally in a steady position guided by the shape and size of the device.

In recent years, new injury concerns have sprung due to repetitive use of media devices. The problem pattern is different in this case. There are some clear differences with industrial work. Firstly, these tasks are voluntary and not necessarily related to productivity or occupation. Secondly, these tasks are not paced, and there is no external incentive to maintain a certain speed. Thirdly, although the motion of the fingers is repetitive, it may or may not be intermittent. There is no necessity to continue these tasks for long hours, but nevertheless, people do browse on the phone and play video games all day. Finally, occupational hand intensive tasks are performed only during the work- hours, whereas hand intensive media tasks can performed at any time of a human being’s diurnal or nocturnal cycle. Individually, one particular media task may not occupy a lot of our time, or may appear harmless, but considering all the media tasks we perform each day, a considerable amount of time is spent daily (Berolo et al., 2011) .

For industrial work, previous concentration of injuries has been mostly at the wrist. In recent years, finger intensive media tasks, especially playing video games and texting, have resulted in injuries occurring mostly at the fingers (Nett, 2009; Karim, 2005; Karim, 2009). Consequently, we concentrate on the kinematics and biomechanics of these finger intensive activities in our study.

1.2 Causes of Strain in Hands and Fingers

Strain and pain in hand and finger joints stem from a number of factors. These factors include but are not limited to: forceful exertion, repetitiveness of motion, sustained exertions, and awkward postures (Keyserling et al., 1993).

Repetitive Motion: Repeating the same motion over and over again (e.g., frequently pressing a button, typing, hammering, sawing etc.) is the most prevalent cause of hand injuries in the industry (Latko et al., 1997). Repetitive motions induce muscle fatigue and inflammation of tendons or tendon sheaths. Over time these ailments can accumulate and ultimately result in disorders known as Repetitive Strain Injuries (RSI).

Forceful Exertions: Applying high force on an object to achieve a desired result (e.g., turning a screw driver by holding it too tight, pushing two parts hard to join them together, pressing a button with excessive force) can result in compression of the sensitive areas of the hand. Excessive compression forces can obstruct blood vessels and nerves that run through the hand, leading to numbness or tingling of the fingers (Sanders and McCormick, 1993).

Sustained Exertions: Sustained exertion of forces (pressing and holding a button, pressing palm against the keyboard to type or for support) has effects similar to forceful exertions. Compressing parts of the hand against a surface for prolonged time can obstruct blood flow.

Awkward postures: Many tasks involve maintaining the hand and wrist at uncomfortable postures. Some of the identified attributes of awkward postures include ulnar deviation, palmar flexion, radial deviation, pronation, hyperextension of the thumb and fingers etc. (Tichauer, 1977, in Sanders and McCormick, 1993). Bao et al. (2006) found repetitiveness to be more associated with measures of strain than forceful exertions.

A combination of these factors may exist for many hand intensive tasks. The small devices that we use in our day to day lives usually require fingers for “tapping” or “pressing” type activities. In many hand held mobile devices, the operation involves flexion/extension or abduction/adduction of the index finger and/or thumb. Although the force required for tapping is not very high for small device operation, prolonged or constrained posture and repetitive movement of fingers may occur together.

Biomechanical model of the hand for tapping type activity (Armstrong, 1976) suggests that, the tensile force required by the finger flexor tendons to perform a “pressing down” activity may be three to four times larger than the actual pressure force experienced at the tip of the finger. Thus a considerable flexor tension is experienced at the tendons. Thus over time, repetitive strain injuries or overuse injuries may occur, as discussed in the previous section.

1.3 Joint Kinematics, Muscle Activity and Ergonomic Analysis: Measures of Strain

To assess the risks of musculoskeletal disorders, there are many approaches that can be adopted. A task can be analyzed using quantitative information about movement (Kinematics), information on how the muscles are being activated (Electromyography), physiological measures such as heart rate, blood pressure, hormone levels etc., or comprehensive standard task analysis methods.

1.3.1 Kinematics of hand and fingers

Our hand has many joints that work like hinges. Each of our fingers has at least two hinge joints that join the finger bones (phalanges). Muscles in our forearm (extrinsic) and hand (intrinsic) provide a rope and pulley action over these hinges so that our fingers and wrists can move (Chaffin et al., 1999). Joint angles at the three major bones of the finger are very important element in two dimensional biomechanical model of the finger (Dennerlein, 1999).

Details about finger joints will be discussed in chapter 3, since kinematics is the focus of this study.

For a finger intensive task, the direction in which the fingers move and the amount of movement with respect to time are important variables. “Kinematics” is a term that encompasses all aspects of the geometry related to the motion of a body (Beggs, 1983).

Any body or mass in motion can be thought to be composed of points and lines whose motion can be described in geometric terms. The common kinematic variables are linear displacements, angles, velocity and acceleration of anatomically relevant projections in the body.

Joint kinematics is a quantitative description of joint posture and joint dynamics necessary for modeling joint movements. Joint kinematics can be a very important indicator of risk of musculoskeletal disorders (Sommerich et al., 1996). Kinematic variables provide information regarding movement direction and speed (velocity), which can be useful to indicate risk of repetitive strain injuries. Kinematic variables for joint movements have been studied for many hand intensive tasks, either to report the movement pattern or to examine effects of other variables on movement patterns. Some interesting examples include the study of typing tasks (Sommerich et al., 1996; Bloemsaat et al., 2003; Cook et al., 2004), Braille reading (Hughes, 2011), synchronization of hand movement during gestures (Braido 2004) and hammering tasks (Cote et al., 2005, Leventhal et al., 2010).

1.3.2 Electromyography

Electromyography (EMG) is the process of recording electrical potential from muscle fibers, this indicates how much and how frequently the muscle is activated during the task. This is, of course another indicator of muscle fatigue (Chaffin, 1999). Details of this method will be discussed in chapter 3.

1.3.3 Ergonomic task analysis tools

Ergonomics is the science that studies the relationships between humans and their work. Ergonomic analyses reveal, among other things, how tasks produce stresses in the human body.

Ergonomic task analysis methods traditionally take into account postural strain variables, such as trunk and neck position, arm and hand flexion angles etc. Rapid Upper Limb Assessment (RULA) is a widely used ergonomic tool to assess the risk of injuries in the upper limb due to posture (McAtamney et al., 1993). This systematic observational method of assessment provides an index to indicate how stressful the posture is.

Repetitiveness of motion is another common variable for assessing bodily strains from tasks with repetitive hand motion. Hand Activity Level (HAL) is a widely used visuo-analog scale to assess repetitiveness of a task that may result in repetitive injuries (Latko et al., 1997; Armstrong et al., 2002). HAL assessment provides a number between 0 and 10 to indicate the risk of repetitive injuries.

Other methods include the Strain Index (Moore and Garg, 1995), which involves measurement or estimation of six task variables. Some other tools used for exposure assessment in the upper body are Rapid Entire Body Assessment (REBA), (Hignett and MacAtamney), Loading on the Upper Body Assessment (LUBA), (Kee et al., 2001), Occupational Repetitive Action (OCRA), (Occhipinti, 1998) etc. HAL may be a useful tool to assess risks of RSIs. Since upper limbs are affected, RULA may be used to assess postural stress.

The current study will focus on applying a multi-faceted approach to analyze micro movement of fingers while performing various media related operations. Some common hand held media device activities among college students will be tested:

- Playing video games on a standard gaming controller,
- Texting on a smartphone, and
- Browsing on a smartphone.

In order to analyze the risk of musculoskeletal disorders, we will take multiple approaches:

- Kinematic variables of finger joint movements will be quantified,

- Electromyography signals will be collected to learn about muscle activation patterns, and
- Ergonomic task analysis methods (HAL and RULA) will be applied as well to assess postural strain.

1.4 Objectives of the Study

The objectives of this study are to:

- Identify and analyze kinematic variables of joints of the index finger and thumb of the dominant hand while performing video games, texting and browsing activities,
- Identify and analyze muscle activation patterns obtained from EMG (Electromyography) signals of two muscles of the dominant hand while performing video games, texting and browsing activities,
- Conduct Hand Activation Level (HAL) analysis and Rapid Upper Limb Assessment (RULA) of the tasks, and obtain indices for repetitive and postural strain, and
- Derive a general relationship between the kinematic variables, EMG muscle strains and postural strain indices mentioned above.

Simply put, we are trying to describe the magnitude and direction of finger motions, and model their relationships with muscle EMG and posture related variables.

Video gaming activity will be tested on a single gaming console/controller and a single game across two types of tasks: a sequenced pre-defined gaming task and a random, spontaneous gaming task. Difference due to device or application change is not within the scope of this study.

Texting and browsing on a smartphone will be performed on one device (differences due to device design is not a study variable), using two kinds of single-fingered postures: using the index finger of the dominant hand to type while the phone is held in the non-dominant hand, using thumb of dominant hand to type while the phone is held in the same hand.

1.5 Study Question and Hypotheses

To be more specific, we are trying to answer the following questions in our study:

- What are the effects of video gaming on finger (thumb and index) kinematics, muscle strain and postural strain of the dominant hand?
- What are the effects of using different fingers (index or thumb) for texting activities on finger kinematics, muscle strain, and postural strain of the dominant hand?
- What are the effects of using different fingers (index or thumb) for browsing activities on finger kinematics, muscle strain and postural strain of the dominant hand?
- Can ergonomic posture analysis tools provide information significantly related to joint kinematics and muscle strain for these finger intensive tasks?

We hope to conduct hypotheses tests and arrive at decisions about:

a. Whether or not there is a significant relationship between kinematic variables and postural strain and between EMG variables and postural strain.
b. Whether or not there are significant differences in kinematics, postural strain and muscle strain for using two types of postures in using smartphones.
c. Whether or not there are significant differences in kinematics, postural strain and muscle strain for using two types of gaming schemes.

1.6 Novelty of Approach

The following aspects delineate originality of this research:

- Kinematic variables and electromyography data for playing video games and texting on smartphones have not yet been reported. It is not known exactly which joints are exposed to maximum risk during these activities.
- Adopting multiple analysis approaches simultaneously will provide multiple measures of risks. This will provide cross validation opportunities.
- A relationship may be established between kinematic variables and risk indices obtained from HAL and RULA. This may indicate prospects of substituting one method for another in analyzing finger intensive tasks.

1.7 Contribution to Knowledge

Video games are usually designed to provide an interactive sense of excitement and pleasure. The virtual arena, in which the game is played, sets the tone and pace of the game, and also the pattern of how fingers are being moved over the controller. By knowing the joint movement patterns and their effects on strain, we can provide information that will be useful to modify video game design. The need for inducing micro-breaks within the virtual realm of a video game may be established. Our analyses may provide information on when and how particular joints are stressed leading to design interventions of both games and controllers. Optimizing finger activity may be considered as a new objective for designing games and controllers.

In case of using smartphones, we will compare two different commonly used single finger methods of texting and browsing. We hope to be able to decide on a preferable posture, and within each posture, we will be able to know the location of maximum strain. Alternate ways of texting and browsing on smartphones may be established.

In short, this study may aid better design of games, gaming consoles and suggest better data entry postures in order to minimize stressful finger movements.

Chapter 2

Literature Review

In this chapter, the literature consulted for this study will be presented according to the pertinent aspects. Research papers and literature relevant to the specific problem in hand were concerned with the following areas: i) studies regarding the demographics, usage and detrimental effects of using small hand held media devices, which provide the rationale for our study; ii) studies where kinematics of hand and/or fingers were reported for various hand intensive tasks, which were consulted to find the appropriate methodology for the current study; iii) literature related to video gaming tasks to enhance our understanding of this highly finger intensive and relatively less researched task; iv) studies that strengthened our understanding of small hand held device use, and v) literature that aided in ergonomic analysis of the problem.

2.1 Demographics and Usage of Small Hand Held Media Devices

Age, or stage in life, is a key variable that influences adaptability to new technology (Sarker and Wells, 2003). The use of small hand held devices is more common among young adults, mainly due to their academic demands and higher ability to absorb new technologies. With the increasing popularity of social networking sites, the use of these devices has become ubiquitous, especially among teenagers and college students.

In a recent study, Berolo et al. (2011) reported demographic and epidemiological information regarding small hand held device use among college students. For a typical day, the highlights of most common mobile device activities among students are shown in Table 2-1.

Table 2-1 Hand-held device use in a typical day of the week (hours)

Activity	**Usage hours** Mean (SD)
Total mobile hand held device use	5.05(6.15)
Browsing	2.77(4.68)
Game controller use	1.23(1.14)
Texting, email and messaging	1.05(1.21)

[Adopted from Berolo et al., Applied Ergonomics 42 (2011)]

The study suggests that more than half of a student's waking life is spent on using small mobile devices. One fifth of that time is spent on gaming.

Since the first gaming console was out in the early 90s, playing video games has been popular among young adults. According to Entertainment Software Association data (2013), 58% of the US population plays video games and 51% of the households have at least one gaming console. Lenhart et al. (2008) reported that 81% of game players are between ages 18-29.

According to a very recent survey, three out of five (61%) mobile phone users in the U.S. own a smartphone, and 78% of the smartphone users are between 25 and 34 years of age (Neilsen, 2013). A later study (International Data Corporation, 2013) identified checking emails as the most frequent smartphone activity, followed by acquiring news and social networking.

Browsing, texting and gaming activities require frequent movement of the fingers. Depending on the design of the device, the activities may require highly repetitive movement of the same few fingers, which is associated with cumulative trauma disorders in hands (Chaffin,1999).

The musculoskeletal symptoms among college students occur mostly at the thumb joints (Berolo et al., 2011). Among the students surveyed, 10.7% reported slight pain at the tip of the thumb, 14.2% reported slight pain in the middle joint of the thumb and 17.1% reported slight pain in the base of the thumb. Moderate pain was felt at the base of the thumb by 8.6% of the students and severe pain by 2.1%. Moderate and severe pain in other fingers was reported by 3.6% and 1.4% of the students, respectively.

2.2 Repercussions of Finger Intensive Media Tasks

Repetitive thumb motion, especially pushing or pressing buttons is associated with discomfort and disorders in the thumb (Fredriksson, 1995, Amell and Kumar, 1999). Bending of the wrist, along with repetition of hand motion, are also considered to be significant factors contributing to ailments like tendinitis, synovitis, tenosynovitis, deQuervain's disease, epicondylitis, etc (Tanaka et al., 2001; Moore, 1997).

Musculoskeletal injuries due to excessive game playing have been reported for various types of gaming consoles. Brasington (1990) reported a case of tendinitis from overuse of the thumb during playing games with a Nintendo, and then coined the term “Nintendinitis”. Later, the term “Wiiitis” was used for repetitive strain injuries of the upper extremities due to excessive use of another gaming console, the Wii (Bonis, 2007; Nett 2009).

One of the most common complaints among video game players is pain and numbness on the tip of the thumb, often known as “PlayStation thumb” (Karim, 2005). Berolo et al. (2011) found a significant statistical association between any pain reported in the middle joint of the thumb of the dominant hand and the time spent on gaming in a typical day.

Texting, on the other hand, is associated with tenosynovitis (Ashurst, 2009; Storr et al., 2007), that is, inflammation of the tendon sheath. Text messaging and browsing activities in smartphones or touchscreen devices require fast movement of thumb and index fingers and awkward hand postures, contributing to musculoskeletal discomfort in fingers. Ming et al. (2006) reported a case of prolonged pain at the base of thumb (first carpometacarpal joint) of a patient due to excessive texting. “BlackBerry thumb” (Gordon, 2008) is a relatively new term that was coined to collectively refer to these symptoms. Karim (2009) argued that the thumb movements in regular texting on regular cellphones are different from “BlackBerry thumb”, and proposed another term “Cellphone thumb” or “Texting thumb”.

2.3 Kinematics of the Hand and Fingers

Kinematics provide information regarding movement, which in turn can be useful for understanding muscle activation, motor control activities and sequence, strain and fatigue, joint pressures, etc.

Much research has been conducted with the aim of reporting kinematic information for different tasks. Baker et al. (2007) reported the kinematics of fingers, thumbs, and hands while using a computer keyboard. Specific variables such as joint angles, velocity, acceleration and translational movement of the wrist were reported. It was suggested that the information provided would be helpful to understand the influence of movements on the musculoskeletal risks of using keyboards. A comparison was made between left and right hand kinematic variables for flexion/extension and abduction/adduction movements. Significant differences were found in hand/wrist posture of the left and right hands. Apart from the thumb, finger joint angles and velocities of the left hand were not significantly different from those of the right hand. Methodology adopted in this study will be followed in our current research. Another study by Kuo et al. (2006) measured finger joint angles and muscle activation for the striking of keys on a computer keyboard. Interphalangeal joints extended and metacarpophalangeal joints flexed during the contact period and vice versa occurred for the lifting period.

For typing tasks, Angelaki et al. (1997) found a non-consistent relationship between the velocity of typing task and the kinematic variables. Using expert typists as subjects, the mean typing rate was varied and hand kinematics was recorded. For some letters and some subjects, the movement variables varied with typing speed but not in all cases. Movement prior to the keystroke was more associated with typing speed than movement after that keystroke.

Movement of fingers and hand during typing is highly repeatable (Flanders and Soechting,1992). This means that the same motion is undergone every time a key is pressed. It was suggested that a pattern may emerge for each key, and therefore sequence of these patterns can be useful in suggesting how words are typed. Soechting and Flanders (1997) later modeled the relationship of hand and finger kinematics for various keystrokes in typing with control activities of the nervous system. Kinematics of a single keystroke was found to be consistent again.

In order to determine a way of measuring translation and rotation of the wrist during radial/ulnar deviation and flexion/extension, Youm et al. (1978) studied kinematics of wrist roentgenographically (x-ray). Cadaver specimens were measured and human volunteers were also used to study bending and rotation of the wrist. Constant measures of carpal collapse and translation of the carpus were obtained. It was concluded that rotation of the wrist occurs about a fixed axis located within the head of the capitates, and that this axis did not change with changing positions of the hand.

Furuya et al. (2011) studied the kinematic variables of fingers and hands of expert piano players. Even in a paradigm of strict time and space constraints, innumerable independent movements of finger joints were found. These movements and velocities were clustered into specific patterns in order to obtain a better understanding of human finger motions. Studies related to finger motions while piano playing was found in other paradigms as well. Goeble and Palmer (2013) studied the joint angle trajectories of hand for fast tempo piano playing and concluded that metacarpophalangeal joints contributed more to fingertip striking motion. Bella and Palmer (2011) later reported that finger kinematics at keystroke was unique for each individual and could be used as an identification variable for pianists.

In addition to being a possible measure of strain, finger kinematics provides important information regarding motor control activities from a neurophysiological perspective. Engel et al.

(1997) used kinematic variables of fingers while piano playing to indicate whether an anticipation of sequence influenced motor control or not. The fact that left and right hand kinematics diverged indicated that strict time sequence was more important than anticipatory sequence.

The postures adopted by the hand and fingers as well as design of the device makes a difference in joint kinematics. Torque and stiffness of joints were found to be different for different postures and design of key switches for a key tapping operation (Jindrich et al.,[1]2004). Joint torque, stiffness, and energy expenditure was more for extended fingers (tapping on a further row of a keyboard).

2.4 Video Gaming

Since the 1970's video games have been a source of entertainment. With advancement of technology, video games have evolved into different types: arcade type gaming, portable gaming consoles, computer games, television- based gaming consoles, physical activity based gaming, and online multiplayer gaming etc. (Kirriemuir et al., 2002).

Extensive and addictive playing of video games has been associated with repetitive strain injuries in the hand, as we discussed in chapter 1. In addition to that, time spent on computer activities, especially game playing, has been reported to be a predictor of low back pain and neck pain among adolescents (Hakala et al., 2006).

Effects of video game playing have been studied mainly from physiological (energy expenditure), psychological (psychosocial and emotional) and demographics perspectives.

Ravaja et al. (2004) studied Electromyography signals from facial muscles, heartbeat, and skin conduction (electrodermal activity) of gamers to understand the enjoyment level in different phases of the game. Surprisingly, emotional responses to the events in the game (positive or negative) were not as expected. Negative events often triggered positive psychophysiological response and vice versa.

Maddison et al. (2007) studied energy expenditure and oxygen consumption for active console video games in which players play with a near-actual opponent depicted in 3-D projections. The energy expenditure was comparable with daily light to moderate exercises because actual movement of upper limbs was involved.

In a similar study, Graves et al.[1] (2008) measured physiological indicators of energy expenditure such as heart rate, movement of upper limbs, etc. for playing Nintendo Wii games. Energy expenditure was found to be greater for boxing games than for tennis or bowling. It was concluded that when both hands were involved, energy expenditure was the greatest. In another study, Graves et al. [2](2008) concluded that energy expenditure was higher for Wii games than for sedentary games (checkers or chess or sedentary video games).

Wang (2006) measured blood pressure, echocardiogram, blood glucose, heart rate and oxygen consumption among children before and after playing a video game. All of these physiological responses increased after playing the game.

Irwin (2011) measured energy expenditure (heart rate, blood pressure, oxygen consumption etc.) and upper limb movement kinematics of children with Cerebral Palsy (CP) while playing active video games. Playing games increased activity of the dominant limb more than the paralytic (diplegic) limb.

In almost all cases physiological responses during or after playing video games showed an increased energy expenditure and upper body movement. Psychological and psychosocial studies on the other hand point to video games as both a source of and an escape from mental stress. Playing video games has also been reported to enhance mental faculties.

It has been known for long that hand-eye motor coordination is better for video game users than non-gamers (Griffith et al., 1983). Boot et al. (2008) studied differences in cognitive performance of expert and non-expert gamers. Contrary to the existing idea, even after practicing games for more than 20 hours, non–expert gamers' cognitive performance was not improved.

Slight improvement was found in mental rotation tasks. It was concluded that inherent group differences had more impact than game playing. Chiappe et al. (2013) found that playing video games 5 hours a week for ten weeks improved system monitoring and communication task performance. They concluded that action video games improve attention ability.

On the other hand, Hossini et al. (2011) found that violent games increase salivary cortisol secretion among adolescent males. This indicates that action or violence based video games increase stress hormone secretion.

Cole and Griffith (2007), in a survey of 912 online gamers, concluded that gamers' social life improved through multiplayer game playing (making new friends, communication etc.). Similar conclusions were reached by Hussain et al. (2009). Another study conducted in Norway found that 4.1% of players had a problematic addiction to gaming (Mentzoni et al., 2011). Addiction to gaming was also found to have high correlations with life satisfaction, anxiety, and depression.

Through extensive literature search, we did not find any study on kinematics of fingers or postural strain assessment during the playing of video games. The closest study that we found recorded head and torso motion to predict motion sickness (Merhi et al., 2007) while playing games on a head-mounted display. Two kinds of games were tested on a head mounted display while participants adopted either a sitting or a standing posture. For *all* conditions, motions sickness persisted.

If kinematic variables can be acquired while a game is being played, players can be aware of their amount of physical activity. Fitzgerald (2011) proposed integration of body kinematic variables *into* a video game so that the players are able to see their physical exercise level as they play the game. Specially designed body suits equipped with body joint markers would be used to attain kinematic data and assimilate it into the video game.

It has been noted that better control over the game is directly related with the sense of enjoyment during the game, and traditional gaming consoles (e.g., Sony playstation) provide better control than active consoles (Nintendo Wii) (Limperos et al., 2011).

Wood et al. (2004) elicited the structural components that are important in video game design. Sound, graphics, humor, realism, background, duration and some other components were considered. However, ease of operation or better control was not included among the structural components. Therefore, in order to improve designs of controllers and games, it is imperative that hand movement and postures while playing games be quantified.

2.5 Operating other Small Hand Held Media Devices

Extensive research has been done in the arena of desktop computer use. Precise ergonomic guidelines already exist for design and use of desktop computers (Imrhan, 1996). For smaller handheld devices, such as mobile phones, netbooks, personal data assistants, smartphones, tablets, e- book readers etc., similar guidelines may or may not be applicable.

Either a “tap” or a “swipe” type movement is enough to accomplish desired browsing and typing activities in modern touchpad or touchscreen type devices. Not all fingers need to be employed for this type of operation. Upper body posture, shoulder and neck muscle activity, wrist and elbow posture and thumb joint movements have been studied to assess strain of this type of task. Some recent developments are discussed here.

In conventional postures, the thumb or index fingers are used to type the message. Spatial constraints exist in case of texting in mobile phones. Although the larger size of more recent smartphones (mobiledevicesize.com) provides a wider space for all the fingers to move, still mostly used postures are uni or bidigital. A recent observational study (Gold et al., 2011) conducted among college students elicited general typing postures and typing styles while the students were using mobile devices in public. 33% of the students used thumb of the dominant hand while holding the device in the same hand. No gender differences were found in typing styles, but typing postures differed between genders. Male students had a higher tendency to protract shoulders, while females had a higher tendency to minimize the elbow angle.

Researchers have studied the tapping operation of fingers from different perspectives. At the contact period of tapping a computer key switch, finger joint kinematics were recorded by Jindrich et al.[2] (2004). The torque on metacarpophalangeal (MCP) and interphalangeal (IP) joints were calculated, and a fitted model suggested that the kinematics and torque were not the same at MCP and IP joints. MCP joint acted both on the IP joint and the tip of the finger to aid the tapping.

Wu et al. (2008) simulated muscle forces in a simulated index finger during key tapping activity. The forces at the tip of the finger was almost equal (ratio 0.95) to the forces acting on extensor digitorum superficialis muscle. This indicates that extension is a more stressful motion.

Texting speed can help us assess repetitiveness of motion. Silfverberg, (2000) predicted that the single thumb text speed (using thumb to type while holding the device in the same hand) for 12- key mobile phones would be 41 words per minute for an expert user. Texting speed will vary from 27-41 words depending on posture and expertise level.

Wang et al. (2009) studied finger orientation on touch surfaces. They observed it is more likely that users will touch a screen obliquely than vertically. For oblique touch, the finger orientation on screen can be fitted into an elliptical shape. From the contact ellipse information, finger orientation vectors can be detected. This information may be further used to detect hand position in holding the device or relative to the device.

Texting posture is influenced by device type, texting style, and screen size of the device (Kietrys et al., 2013). Upper limb muscle activities, neck posture, and wrist posture were studied during use of keypad and touchscreen type devices. For keypad devices, thumb and extensor muscle forces were larger than for touch screen type devices. Greater wrist extension was found for touch screen type device use. For single handed texting (using thumb), thumb and wrist extensor muscle forces were found to be greater compared to when both hands were used. Larger touch screen size resulted in greater wrist extension, ulnar deviation, and cervical flexion.

Size and type of device was also found to influence performance on touch-screen type tablets. Pereira et al. (2013) examined usability and fatigue, neck and arm postures of the non-typing hand, and forearm electromyography of thirty small handed subjects while they performed data entry tasks on eight different types of tablets and three different stylus conditions. Usability was better for smaller and medium sized tablets held in portrait orientation. No significant changes were found in productivity for different sizes of devices.

One of the advantages of small touch screen type devices is that they can be held in any orientation the user feels comfortable with. We can use them while sitting, standing, lying, holding in hand, on lap, etc. Thomas et al. (2002) tested which position and posture was suitable for use of touch pad type mouse. A small touch pad was placed on different parts of the human body while subjects adopted different postures (sit, stand, kneel) and performed a target reaching task. Timing and error rate measured from the task indicated that for sitting, kneeling or standing position, front of thigh (lap) was the best position for swiping type task.

Individuals with or without musculoskeletal symptoms perform texting tasks differently (Gustafsson et al., 2010). A study of 54 participants concluded that individuals with musculoskeletal symptoms performed texting tasks in a more close to neutral posture with back and neck support most of the time. EMG from six muscles of the hand and forearm were tested, and thumb abduction/adduction was measured. There was clear difference in muscle activity and kinematics of thumb between symptomatic and asymptomatic group. But the authors also stated that these differences in posture and muscle activities may be the cause, rather than the results, of musculoskeletal symptoms.

Lin et al. (2009) studied psychophysiological measures of not only text typing but also text receiving. College students, who used texting very frequently, were the participants of the study. During a specific set of texting protocols, including receiving texts, the participants were monitored for the following physiological variables: electromyography (SEMG) from the shoulder (upper trapezius) and thumb, blood volume pulse (BVP) from the middle finger, temperature from the index finger, and skin conductance (SC) from the palm of the non-texting hand, and respiration from the thorax and abdomen. Eighty three percent of the participants reported hand and neck pain during texting. Participants were unaware of it, but breathing patterns and arousal level changed when a text was received.

Kim et al. (2013) tested different key sizes on virtual keyboards. Typing speed, shoulder muscle activity, wrist kinematics for both hands were recorded while subjects typed a predetermined sentence on virtual, touch type keyboards with four kinds of key sizes. Smaller key size (13x13mm) was found to cause more wrist extension, slower typing speeds, and greater shoulder muscle activity.

Although shoulder and wrist muscle EMGs and upper extremity kinematics have been studied for thumb texting, comparison of two single fingered postures of the same hand has not been done before. Specifically single and bi-fingered movement kinematics for texting and browsing activities on touchscreen phones still have not been quantified. Comparison of thumb versus index finger use may result in useful suggestions regarding mobile device usage.

Our approach also includes ergonomic posture analysis, which has not been incorporated in previous analyses.

2.6 Ergonomic Analysis Tools for Hand Intensive Tasks

The strain Index (Morre and Garg, 1995) has been a reliable tool for assessing risk of repetitive strain injuries in upper extremity for industrial works. The strain Index involves measurement of six task variables, which may not be acquirable for many tasks. In 1997, Latko et al. proposed and validated an observational method based on expert opinion, named Hand Activity Level (HAL). In 2001 American Conference of Governmental Industrial Hygienists

(ACGIH) proposed threshold limit values (TLV) based on hand activity level (HAL) and normalized peak force (PF).

HAL and ACGIH HAL TLV were found to be used to assess tasks in diversified fields including foundries (Armstrong et al., 2002), automotive plants (Ebersole et al., 2006; Werner et al., 2005; Drinkaus et al., 2005; Ciarrocca et al., 2012; Sancini et al., 2013 etc.), poultry industries (Caso et al., 2007), dairy farms (Patil et al., 2010), etc.

Rapid Upper Limb Assessment (RULA) is another ergonomic assessment tool to assess the risk of upper extremity disorders due to work load (MacAtemney et al., 1993). Not unlike HAL TLV, this tool also is easy to use and does not require any special equipment of measurements. Neck, shoulder, forearm, and hand postures are assessed by visually observing the tasks, and risk indices are assigned for each part of the body. This leads to a final RULA number that indicates the overall risk of injury for the task.

Using multiple risk analysis tools together is not uncommon for industrial tasks. For postural analysis, RULA was used by Speilholz (2008) to compare RULA scores to HAL TLV scores with respect to laterality. Borg scale, Strain Index, RULA, and NIOSH tables were used by Albers et al. (2007) to assess risks of injuries in roller screeding tasks.

A literature review of thirty recent papers (Proma and Imrhan, 2013) revealed that a simple- to- use posture analysis tool such as HAL was, in most of the cases, not sufficient to acquire a well validated comprehensive view of hand intensive tasks. In most of the cases RULA and HAL were used together to assess the risk of repetitive strain in industrial work. Ergonomic risk analysis tools have been used mainly on industrial work.

The tasks we are interested in in our study (playing video games, texting and browsing) are repetitive and very much at risk of injuries. We think that by applying Hand Activity Level and Rapid Upper Limb Assessment, we will be able to arrive at important indices of risk of repetitive strain. These indices may aid in validation of our findings from kinematic and muscle strain data.

Chapter 3

Methodology: Data Collection

In this experiment, aimed to study some popular media activities among college students that may pose a risk of repetitive strain injuries. Upon observation, finger movements may seem irregular and hectic for these tasks. We are looking for patterns in finger movement that may indicate stress. The objective was to obtain kinematic variables, muscle activity, and postural strain of the hand while small media devices were used. These variables are indicators of risk of repetitive strain injuries and have not yet been examined for video gaming or smartphone use. If a relationship among these variables can be established, the risk of injuries can be authorized even more strongly.

The activities chosen are: video game playing in a gaming console and texting and browsing in a smartphone. In this chapter, we discuss the methods of collecting data for our study. The study protocol was approved by University of Texas at Arlington (UTA)'s Institutional Review Board (IRB).

3.1 Tasks to be studied

To maintain integrity of the experiment and to minimize variances due to individual task performances, the task description was standardized. Each task was performed in a pre-defined sequence, and the task environment (workspace) was kept the same for all of the tasks.

3.1.1 Video Gaming

The task of video-gaming involved playing video games on a Sony Playstation III gaming console. The same controller was used by all the subjects, so device type was not a variable of study in this experiment. The game used for this experiment was "Facebreaker" (Electronic Arts, CA, 2008), a relatively basic 2-player boxing game suitable for ages 10 and up. Two gaming protocols were performed:

a) The Sequenced Protocol: In this protocol, the subject played the game in a practice session, the player (avatar in the game) was pre-chosen, the opponent (computer) was also pre-chosen. The opponent was placed in a "dummy" mode, so that the he will not attack the main player. The session could be played using only thumb and index finger of the right hand, and there was no need to use the left hand at all. It was this feature of the game that made it a good option for predefined sequencing and thereby a suitable option for this experiment.

In this scenario, a predefined set of attacks (punches, high punches, low punches, throws, etc.) was to be performed by the player. In the game controller, the exact sequence to be played or the buttons to be pressed are shown in Table 3-1. Figure 3-1shows the button positions in the PSIII controller and the hand position.

Table 3-1 Sequenced game protocol

Sequence	Move	Representation in game
1	Press "□" 8 times	Punch (up)
2	Press "X" 8 times	Punch (down)
3	Press "O" 8 times	High punch
4	Press "Δ" 8 times	Throw
5	Press and hold "□"	High parry
6	Press and hold "O"	High punch
7	Press and hold "Δ"	High throw
8	Press and hold "X"	Low parry

Table 3-1. Continued

9	Press R1 twice	Block
10	Press R1 and "□" together	Block + High parry
11	Press R1 and "X" together	Block + low parry
12	Move joystick in left, right, up, down and counterclockwise.	None

In the sequenced protocol, these twelve moves were performed. The subjects were not given any time limit; they played at their own pace. The subjects were asked to practice the sequence properly before the experiment. They were asked to practice as long as they needed to perform the sequence almost automatically. When the subjects confirmed that the sequence was well practiced, and they were ready for the real experiment, the following performance was recorded:

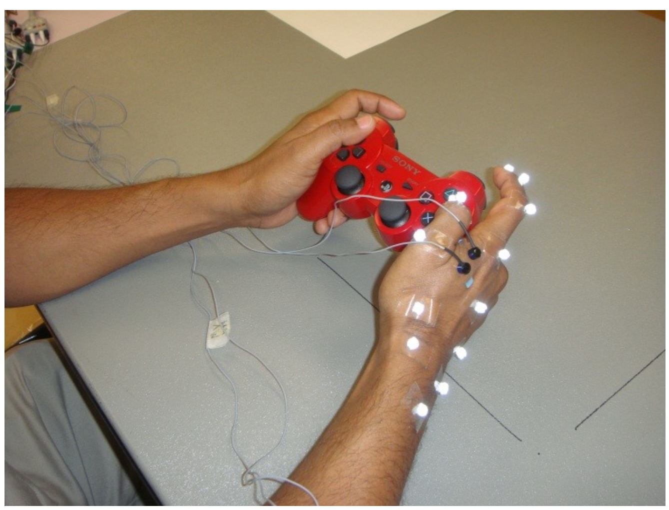


Figure 3-1 Buttons and hand position on PS III controller

The Natural (real game) Protocol: After the predefined sequence, the opponent of the game was placed in an "offensive mode", while the game was still in a practice session. In this situation, the subjects were asked to do whatever was needed to win the game. The players were told that they could press any button in the controller at any pace they wanted. Their only objective would be to hit the opponent in any way they can and to win the game. In this scenario, subjects were unaware of the data being recorded. In

Figure 3-2, a subject is performing the game sequence; a glimpse of the game can be seen on the TV screen.

Figure 3-2 A subject playing video game

Task Environment: The subjects sat on a chair in front of a table, held the controller in both hands at a specified position on the table and then performed the game. The table was 75 cm high, 75.5 cm in length and 183 cm wide. The chair seat was 44 cm high from the floor. There was no arm rest on the chair, but subjects could rest their arms on the table. This workspace arrangement matched with ergonomic guidelines for sitting work (Cornell University Ergonomics

Web, 2013) and was comfortable for the subjects. A 40 inch HD screen television was used to display the game. Distance from the television to the viewers' eye was approximately 186 cm. The task space was surrounded by six VICON cameras to record hand motions. Another HD camera was placed on the TV stand to collect video of the task (movie like data). The real task area can be seen in Figure 3-3.

Figure 3-3 Task environment

A detailed schematic of the task environment is shown in Figure 3-4. Movement of each joint of the thumb and index finger was collected from a VICON video data collection system. Positions of the VICON cameras can be seen in figure. Electromyography (EMG) data was collected from two muscles using an EMG amplifier system, and additional movie type video data was collected from a point and shoot video camera.

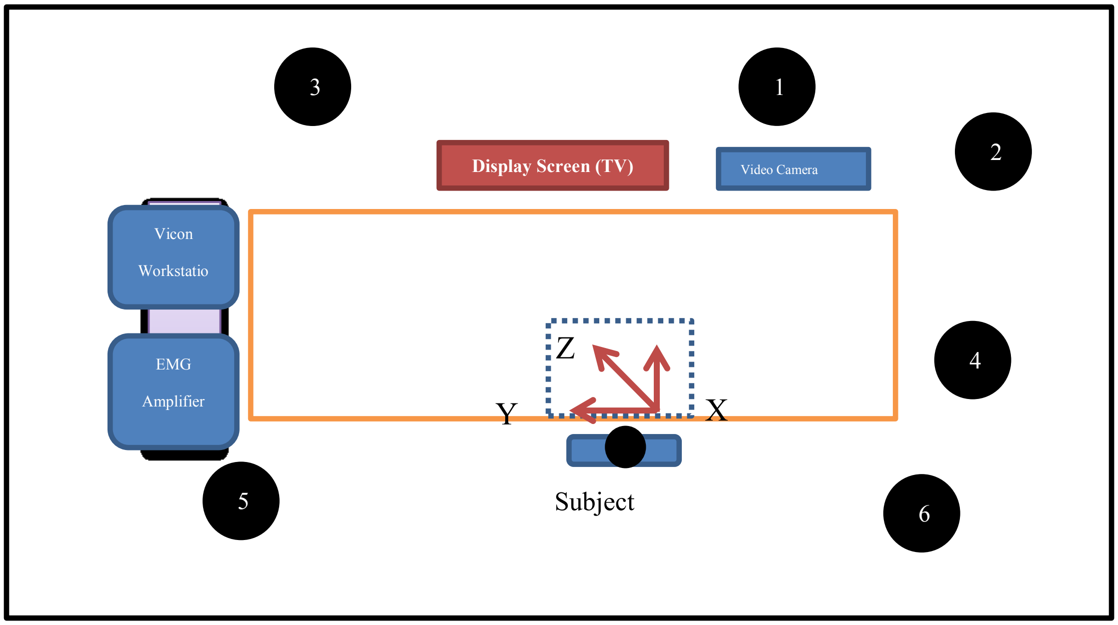


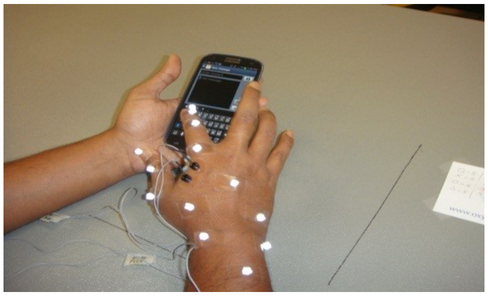
Figure 3-4 Task environment, camera positions and direction of motion

3.1.2 Texting

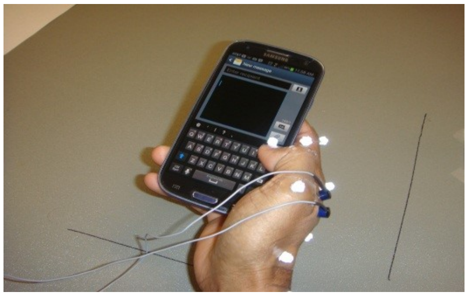
The second task to perform was texting on a smartphone. Two common postures of single-fingered typing were tested for this task:

a) Holding the phone in left hand and texting with the right index finger (Figure 3-5 a)

b) Holding the phone in right hand and texting with the right thumb (Figure 3-5b)



a. Single fingered texting using index finger



b. Single fingered texting with thumb

Figure 3-5 Texting postures

Differences due to design of device were not within the scope of this study; therefore, the same device (Samsung galaxy S III phone) was used to test texting for two postures. The phone was held longitudinally (longer side used to hold the pone) at all times.

For texting, subjects were asked to type the following sentence using postures a,and b.

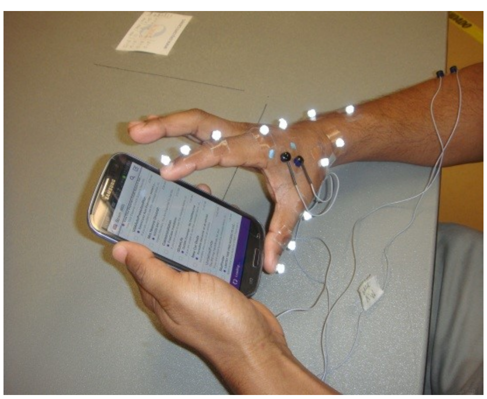
“A quick brown fox jumps over the lazy dog”

This sentence was chosen because it incorporates all the 26 letters in English (englishforums.com, 2005). This unique pangram has been widely used to test hand writing speeds, typing on keyboards, and even touchscreens (Ziviani, 1984; Sears, 1992; Roeber, 2003)

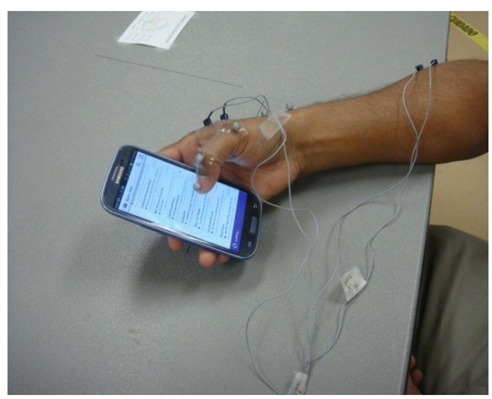
The subjects were instructed to type at their own pace. No time constraint was added. The subjects were also instructed to keep on typing in case they made a mistake and were told not to press backspace or delete keys, as per standard testing procedures (Baker et al., 2007).

3.1.3 Browsing

Two single fingered browsing actions were tested: a) Holding the phone in the left hand and browsing with the index finger of the right hand, and b) holding the phone in the right hand and browsing with the thumb of the same hand (Figure 3-6 a and Figure 3-6b).



a. Single fingered browsing with index finger



b. Single fingered browsing with thumb

Figure 3-6 Postures for browsing

The task simulated the single fingered actions similar to checking emails (browsing through inbox). For each posture, the subjects were asked to browse through the inbox by swiping three times from bottom to top (as if browsing through) and then tapping once to open the bottom-most email.

Therefore each subject performed six tasks:

a. Playing the video game in predefined sequence,
b. Playing the video game in a natural manner,
c. Texting with thumb of their dominant hand while the phone was held in the same hand,
d. Texting with index finger of the dominant hand while holding the phone in the other hand,
e. Browsing with the thumb while the phone was held in the same hand, and
f. Browsing with the index finger of dominant hand while holding the phone in the other hand.

3.2 Subjects

More than eighty percent of video game players are males of age 18-29 (Lenhart et al., 2008). Ten male college students, all of whom were right handed, performed all the tasks. Subjects were well acquainted with Sony PlayStation gaming, and confirmed that they played video games for at least 2 hours per week. In addition, three female right handed students participated in the tasks. Hand measurements (length of joints) and vital statistics (height, weight, age) of each subject were recorded prior to the study. Descriptive statistics of the subjects are provided in Table 3-2.

Due to the intricate nature of the data collection procedure, not all subjects' data could be extracted for all the tasks. Especially, we could not extract all the variables needed from all subjects for texting and browsing tasks. Consequently, non parametric statistical methods were used later to analyze obtained data.

Table 3-2 Descriptive statistics of the subjects

Mean (standard deviation) of males and **females**												
Demographics			Length of hand joints (mm)									
Height (cm)	Age (Years)	Weight (Kg)	Hand length	width at knuckles	fingertip to root digit 1	fingertip to root digit 3	fingertip to root digit 5	Tip to IP 1	IP 1 to MCP 1	Tip to DIP 2	DIP 2 to PIP 2	PIP 2 to MCP 2
176.55 (5.23)	27.5 (4.23)	76.2 (13.03)	186.23 (10.05)	83.3 (5.77)	63.06 (3.8)	80.8 (5.26)	60.37 (5.01)	33.38 (2.4)	32.27 (2.42)	25.62 (2.03)	21.86 (2.34)	24.88 (2.47)
90.89 (121.15)	***15.87 (16.46)***	***44.62 (44.67)***	***98.14 (124.58)***	***44.54 (54.83)***	***33.43 (41.91)***	***43.03 (53.42)***	***32.69 (39.15)***	***17.89 (21.91)***	***17.35 (21.11)***	***13.83 (16.69)***	***12.1 (13.81)***	***13.68 (15.85)***

We may consider that there was a random assignment of subjects to tasks in that, we used ten subjects' data for sequenced and natural gaming; eight subjects' data for index finger texting; seven subjects' data for thumb texting, and five subjects' data for index finger browsing and thumb browsing tasks.

3.3 Data Collection Procedure

3.3.1 Joints and Muscles of the Hand

In order to understand the kinematics of fingers, we first need to understand the joints of fingers. The hand is proximally bounded by carpal bones adjacent to the wrist. Metacarpal bones are joined with the carpal bones through carpo-metacarpal joints (CM joints), metacarpals and phalanges (Moore, 1992). Figure 3-7 shows the joints. The thumb (digit 1) has a metacarpal bone, and two phalanges. The joints between metacarpals and phalanges are known as metacarpophalangeal (MCP) joints. All fingers have these. The joints between phalanges are referred to as interphalangeal (IP) joints. Each of the fingers other than thumb (digits 2 to 5) has two interphalangeal joints: proximal (PIP) and distal (DIP).

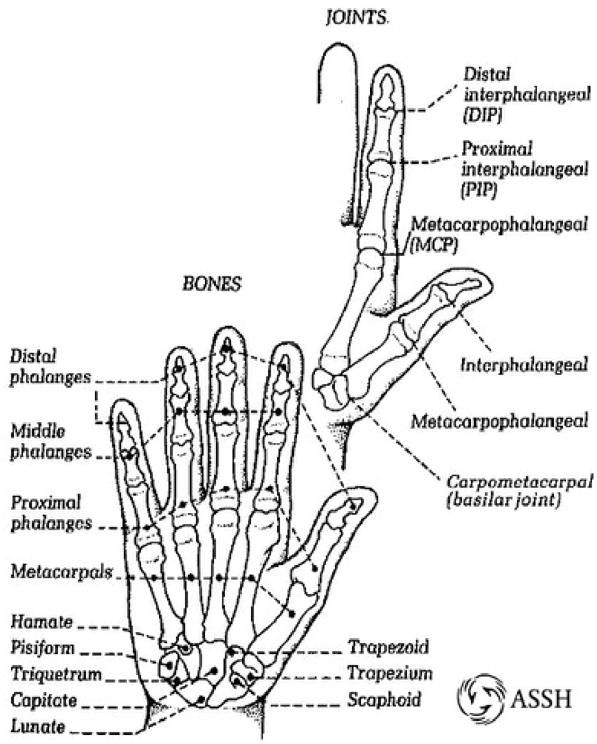


Figure 3-7 Joints of the hand [source: American society for the surgery of the hand www.assh.org]

In the current experiment, joint movements of the thumb and index finger were studied. Movements of two joints in the thumb (MCP1,PIP1) and three joints in the index finger (MCP2, PIP2 and DIP2) were recorded.

Muscles studied for this research were Extensor Digitorum (ED) and First Dorsal Interosseous (FDI) as shown in Figure 3-8. The extensor digitorum is a large muscle located on the posterior surface of the arm. It extends the four digits of the hand other than the thumb. Particularly, it extends the proximal phalanges. It also assists in abduction of the index, ring, and little finger, and abduction and extension of the wrist (Kendall and McCreary, 1982).

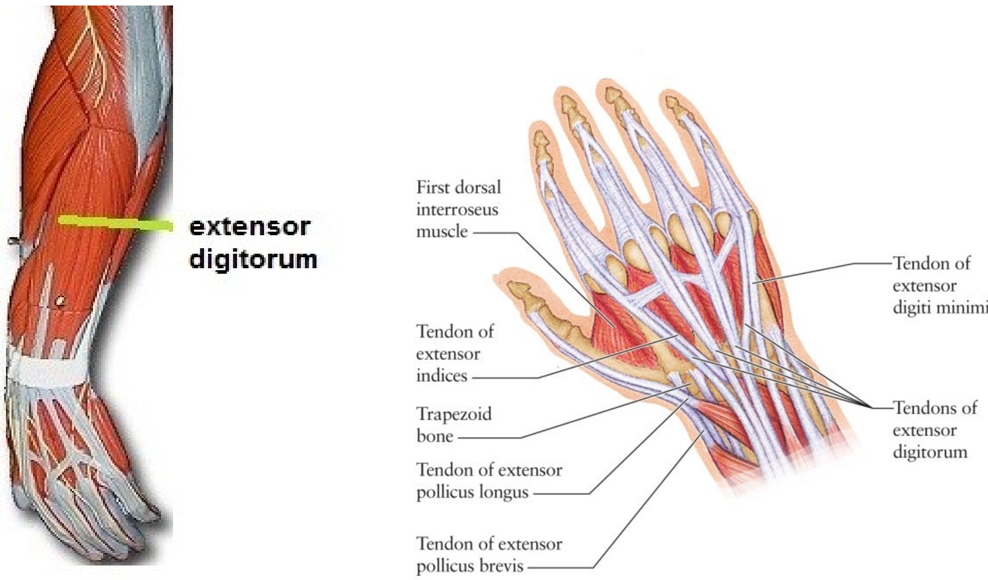


Figure 3-8 Muscles of the hand

(source: 1. http://legacy.owensboro.kctcs.edu/gcaplan/anat/notes/extension%20dig.jpg
2. http://3.bp.blogspot.com/-MpOwLheHgG4/Tgk1aD1nu5I/AAAAAAAAACY/hCXaexHTpMk/s1600/DiagramFLAT.jpg)

The first dorsal interosseous muscle is an intrinsic (within hand) muscle of the hand, and its primary function is to conduct abduction/adduction of the index finger. The reflective markers and video game controller limited the space available for the attachment of more electrodes. It was difficult to place EMG electrodes on other intrinsic muscles of the hand. Therefore the EMG analysis of the study was somewhat limited.

3.3.2 Hand Preparation

Subjects' hands were wiped thoroughly with alcohol before placing the markers and electrodes on specific points of the dominant hand. Thirteen (three on thumb, four on index finger, three on hand and three on wrist area) reflective markers of 4 mm diameter were placed on the right hand of the subject . Prior to electrode placement, selected area of the hand was shaved and well rubbed with alcohol to clean the area. Two sets of EMG (Electromyography) surface electrodes were placed on hand and arm: one set on First Dorsal Interosseous (muscle on the other side of the palm right below the index finger), and one set on Extensor Digitorum (large muscle in the middle of forearm) as shown in Figure 3-9. Double sided tape was used to place the markers and the electrodes on the surface of the hand.

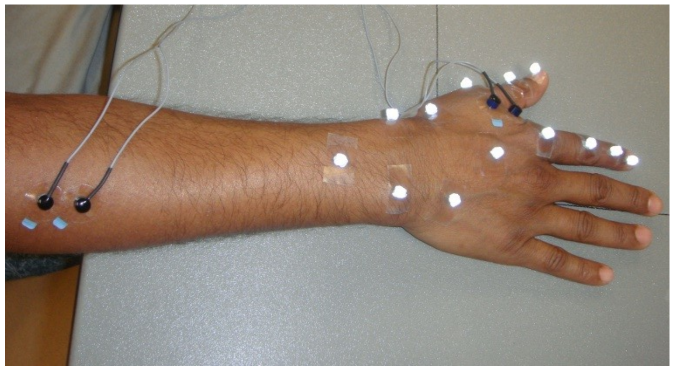


Figure 3-9 Marker and EMG electrode positions on hand

3.3.3 Kinematic Data Collection on VICON

The Vicon 460 motion capture system (Vicon Motion Systems, 2002) was used to perform motion capture. The system records movement by an array of video cameras in order to reproduce a 3-D image digitally. The system comprises six high resolution VICON cameras (Fig 3-5). The cameras lenses are surrounded by LED (Light Emitting Diode) strobes. Small round beads with reflective coating known as reflective markers need to be placed on the part of the body whose motion is to be captured. As the body part moves, light from the LEDs is reflected back into the camera lens and strikes a light sensitive plate creating a video signal. The software used in conjunction with motion capture is called “Workstation”. This is used to collect and process the raw video data. It takes the two-dimensional data from each camera and then combines it with calibration data to reconstruct the equivalent digital motion in three dimensions.

Vicon camera positions and focus were selected by trial and error until a steady and reliable image with all thirteen markers was clearly captured. Not all cameras were placed at same height. Two cameras (4 and 6) were positioned a little higher than the sitting height of the subjects, so that hand movement could be viewed closely. Three (1,2,3) cameras were mounted near the ceiling, and one camera (5) was mounted and focused to capture direct top view of the task area.

Marker placement on hand was adopted from Baker et al. (2007), with slight alteration for our two-fingered tasks. Markers were placed so that the index finger would be represented by three links, and the thumb would be represented by two links. The wrist would be represented by a triangle and the dorsal surface of the palm would be represented by another triangle. Figure 3-10 shows the marker positions and symbols on hand. The symbols FR1, FR2, FR3 and FR4 represent the markers on the index finger. TR1, TR2 and TR3 are on the thumb. HRAD, HULN and MHAND complete a triangle on hand and WRAD, WULN and FARM complete a triangle on wrist. The positions of the markers are described in Table 3-3.

Table 3-3 Symbols and positions of markers on hand

Symbol	Position on hand
FR1	MCP joint of Index finger
FR2	PIP joint of index finger
FR3	DIP joint of index finger
FR4	Tip of the index finger
TR1	MCP joint of thumb
TR2	IP joint of the thumb
TR3	Tip of the thumb
HRAD	Proximal second metacarpal
HULN	Proximal fourth metacarpal
MHAND	Second metacarpal (approximately)
WRAD	Radial styloid
WULN	Ulnar styloid
FARM	A point in forearm between radius and ulna to complete the triangle

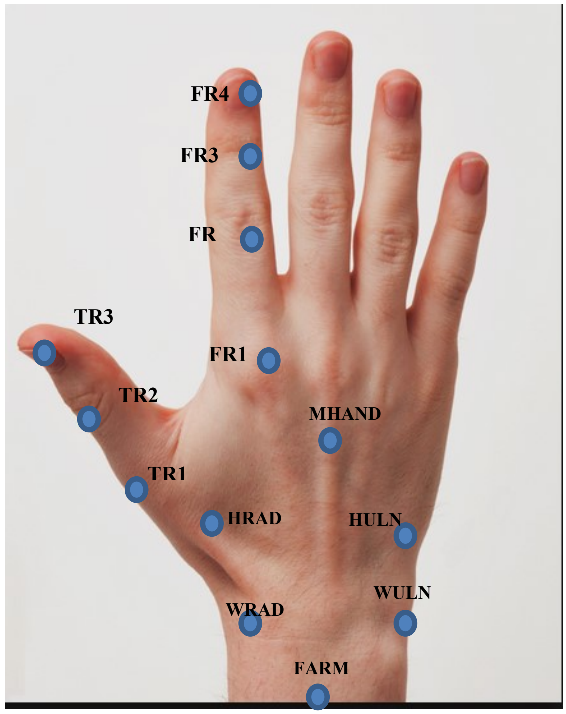


Figure 3-10 Marker position and links of the hand

As the subjects performed assigned tasks, video data was collected on the VICON system at a rate of 60 Hz. There were six task videos for each subject. The videos were reconstructed in *workstation* software to obtain the marker movements in 3-D space. The first few frames of each video were cut off until all thirteen markers were visible in the reconstructed data. Each marker in each frame was identified in the software. The software was used to fill gaps by applying the Woltering filter routine and extracting the data into an ASCII file. In addition to kinematic data, EMG signals were also processed by the workstation software. Raw EMG signals (mV) obtained from the muscles were transferred to the same ASCII file.

3.3.4 Electromyography Data: The BIOPAC EMG System

BIOPAC EMG amplifier system was used to collect electromyography data from two muscles. The BIOPAC MP 150 system has maximum output voltage of ±10V, accuracy of ±.003%. Two channels with maximum capacity of 5 KHz were used to acquire data from two muscles. The EMG readings were amplified 1000 times and filtered with a bandwidth of 10-500 Hz. Shielded 4 mm electrodes were filled with electrode gel and were attached to the hand with double sided tape. An unshielded pinch-lead type electrode was used as ground on the neck.

The electrical activity of the first dorsal interosseous and extensor digitorum muscles were recorded using two channels. Prior to electrode placement, hair was shaved from the skin and was lightly abraded and cleaned by rubbing alcohol to reduce signal impedance. The longitudinal axis of the electrodes was aligned parallel to the length of the muscle fibers. The ground electrode was positioned on the bony projection of the c7 vertebra on the neck. EMG data were sampled at 1080 Hz using a National Instruments (Austin, TX) PCI-6229, 16-bit analog-to-digital converter with a voltage range of ±5 V.

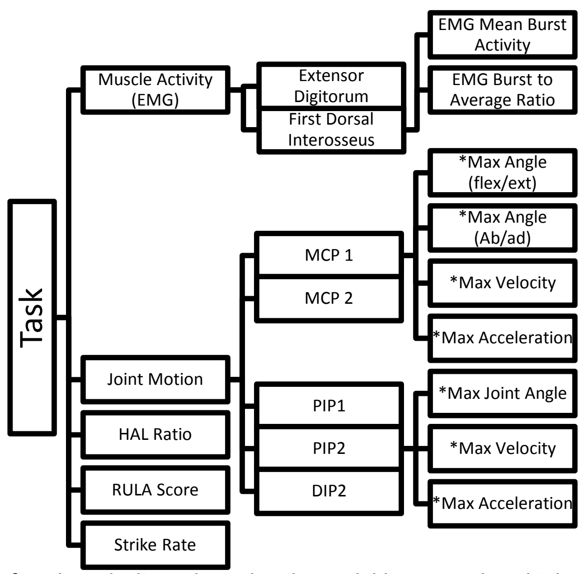
3.3.5 Task Videos

Real time video data was collected for each subject performing each task. A Canon Powershot camera with 12 megapixel resolution was placed in front of the task area to collect high definition video data. Later, these video images will assist in HAL and RULA assessment for posture analysis. These videos will also help to identify markers and phases of tasks when we analyze data in Vicon.

Chapter 4

Data Analysis Methods

For three kinds of hand-intensive media tasks, we collected raw data to obtain joint kinematics, EMG muscle activity and postural strain. The variables that we want to obtain for each task from these raw data are shown in Figure 4-1. In this chapter, we will discuss the definition and procedure of acquiring these variables.



*[Average of angle, velocity and acceleration variables were also obtained]

Figure 4-1 Variables obtained from each task

For ease of discussions, will refer to the five finger joints as: MCP1 (metacarpophalangeal joint of the thumb), PIP1 (interphalangeal joint of the thumb), MCP2 (metacarpophalangeal joint of the index finger), PIP2 (proximal interphalangeal joint of the index finger), and DIP2 (distal interphalangeal joint of the index finger).

4.1 Kinematic Variables analysis

4.1.1 Direction of Movement

Standard biomechanical directions were followed for finger flexion/extension and abduction/adduction. For any finger-joint, flexion occurred when there was a decrease in the joint angle, and extension occurred when there was an increase. While tapping a button, flexion occurs when the finger reaches the button, and extension occurs when the finger moves away from the button after the key has been pressed. Finger abduction/adduction was taken as movement toward or away from the other fingers (moving left and right).

4.1.2 Joint Angle, Velocity and Acceleration

Motion data from Vicon Workstation was interpolated and lowpass filtered at 3 Hz frequency. This would prevent phase distortion. The motion data obtained from VICON workstation was analyzed using Visual 3D software version 6.0. A static trial was recorded for each participant, where they simply held their hand still on the surface of the table. From this static trial, positions of the markers were identified and used to construct hand segments in visual 3D software. The following hand segments were constructed, as shown in Figure 4-2: thumb base, thumb12, thumb 23, finger12, finger 23 and finger34 and hand. Thumb base was a segment that simply connected the first MCP1 joint to the hand. Thumb 12 connected MCP1 and PIP 1 joints, and thumb 23 represented the distal phalanx of the thumb. Similarly, finger12 joined MCP2 and PIP2, finger23 joined PIP2and DIP2, and finger 34 represented the distal phalanx of the index finger. The hand segment represented the dorsal plane of the palm in general. Each segment had its own local coordinate system. The coordinate systems were kept as aligned together as possible. The X, Y and Z directions were defined as follows: the transverse plane of the body was on (x,y) plane, coronal plane was on (y,z) and sagittal plane was on (x,z) plane.

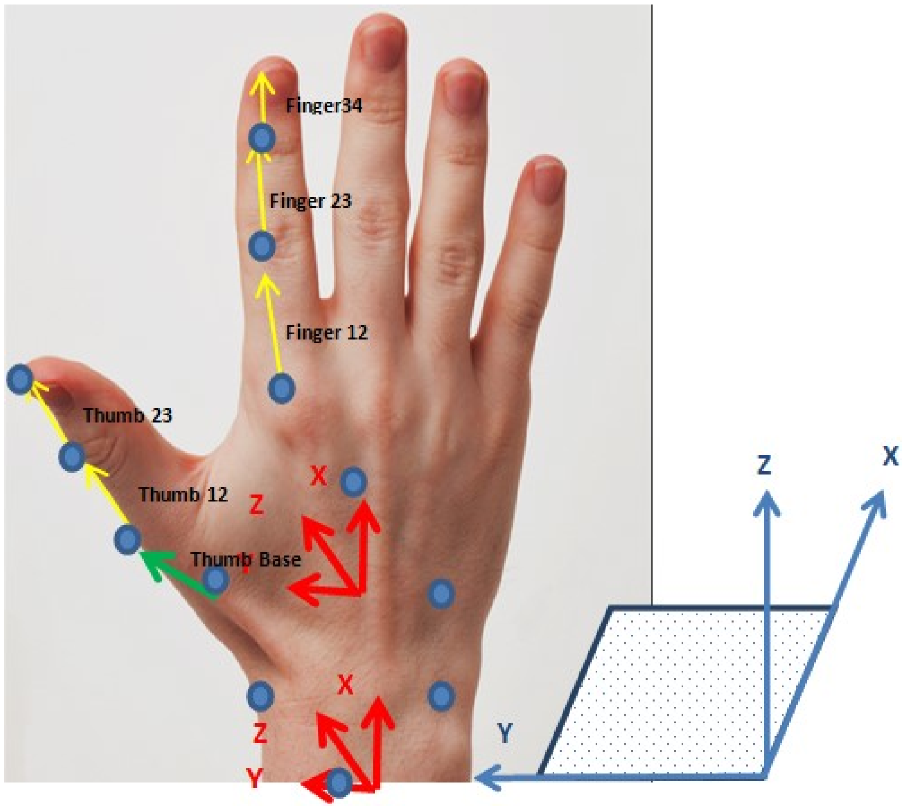


Figure 4-2 Hand segments and axes

Joint angles (Degrees) were calculated as Euler angles. The inverse kinematics principles (C-Motion Research Biomechanics, “Inverse Kinematics”, 2014) were used to calculate Euler angles of each segment with respect to X, Y and Z axes. The joint angle definitions in terms of location, reference segment, Euler axes and segment in motion are summarized in Table 4-1. The X Euler angles represented flexion-extension, and Y Euler angles represented abduction adduction of the finger. For both flexion-extension and abduction- adduction joint angles, we focused on the amount of the angular displacement, rather than the direction (positive/negative). Consequently, we used the absolute values of the joint angles for our analyses.

Table 4-1 Joint angle definitions

Joint location and motion	Joint angle abbreviation	Euler axis	Reference Segment	Motion Segment
Metacarpophalangeal joint of the thumb, flexion-extension	MCP1 f-e	X	Thumb base	Thumb 12
Metacarpophalangeal joint of the thumb, abduction-adduction	MCP1 ab-ad	Y	Thumb base	Thumb 12
Interphalangeal joint of the thumb, flexion-extension	PIP1f-e	X	Thumb 12	Thumb 23
Metacarpophalangeal joint of the index finger, flexion-extension	MCP2 f-e	X	Hand	Finger 12
Metacarpophalangeal joint of the index finger, abduction-adduction	MCP2 ab-ad	Y	Hand	Finger 12
Proximal interphalangeal joint of the index finger, flexion-extension	PIP2 f-e	X	Finger 12	Finger 23
Distal interphalangeal joint of the index finger, flexion-extension	DIP2 f-e	X	Finger 23	Finger 34

Joint velocities (Degrees/s) and accelerations (Degrees/s^2) were computed with the Visual 3D software by differentiating the angles and velocities respectively. Reference and motion segments were as described before.

For any given task, subject and joint, angle, velocity and accelerations were calculated for each video frame of data. We calculated two types of averages for each task:

a) Average : First, for each task, subject and joint, the average value (of a joint motion variable) was calculated across all the frames of data. Then, the average joint angle/ velocity / acceleration was obtained by averaging across all subjects.

b) Average Maximum: First, for each task, subject and joint, the maximum value (of a joint motion variable) was obtained across all the frames of data. Then, these values were averaged across subjects to obtain average maximum joint angle/ velocity / acceleration.

4.2 EMG Variables

Raw EMG signals obtained from workstation software were processed in Visual 3 D software. The raw EMG signals were rectified to get a unidirectional view. The rectified data was then lowpass filtered using Butterworth filter of 6 Hz cutoff frequency. Thus a consistent and comprehendible EMG pattern was obtained.

The EMG patterns found for all the tasks were not similar. In some cases, the tasks required a "burst" of muscle activity at some frames, while other frames indicated relatively small amount of muscle effort. For some tasks, however, there was no discernable "burst" of activity. To be consistent with our video data analysis, we adopted Lay et al.'s (2006) method with some modifications.

EMG signals were collected at 1080 Hz, while the video data was taken at 60 Hz. Therefore, 18 frames of EMG data were found for each frame of video data. We first calculated the average value of EMG signals for each of these 18 frames (average EMG per frame, M_f). The overall average EMG (M_a) for each task was found by: $M_a = (\sum M_f) /$ number of video frames.

To get an idea about the muscle effort expended in the sections where an EMG "burst" was found, we calculated another average EMG value, "burst average", M_b defined by:

$M_b = (\sum M_f$, where $M_f > M_a) /$ (number of video frames where $M_f > M_a$)

Figure 4-3 shows the average (Ma) and burst average (M_b) amplitudes of EMG for a subject while performing the sequential video gaming task.

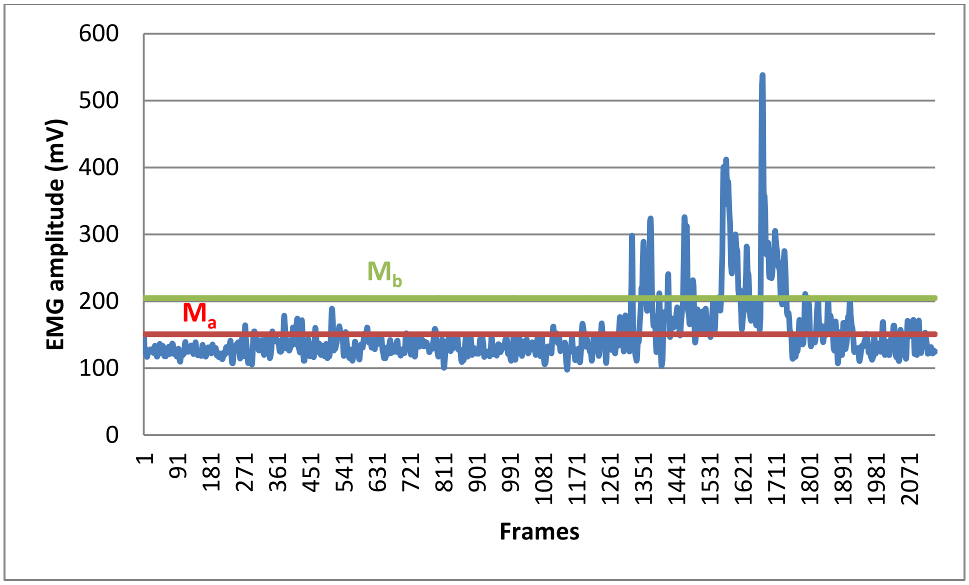


Figure 4-3 EMG average amplitude calculation

Thus, the EMG "burst to average ratio", M_b/M_a would represent a comparison of the higher muscle efforts required for the task at some point, to the overall average muscle effort.

4.3 Analyzing Posture

Two kinds of ergonomic task analysis will be performed for each task: Hand Activity Level and Rapid Upper Limb Assessment.

4.3.1 Measure of repetition: Strike Rate

From the task videos, the number of times a finger touched the screen (strike) was counted and the time was recorded with a stopwatch. Then the strike rate was calculated from:

Strike Rate (Strikes/sec) = Number of times finger touches the screen during the task / total time of the task in seconds.

Strike rates were averaged across subjects to get an average strike rate for each task.

4.3.2 Hand Activity Level (HAL)

Hand Activity Level (HAL) is a subjective scale that ranges from 0 to 10. A task involving repetitive movements of hands can be assigned a value from 0 to 10 based on exertion frequency, speed of work and recovery time (Latko et al., 1997). Figure 4-4 shows the scale, as used by trained ergonomists.

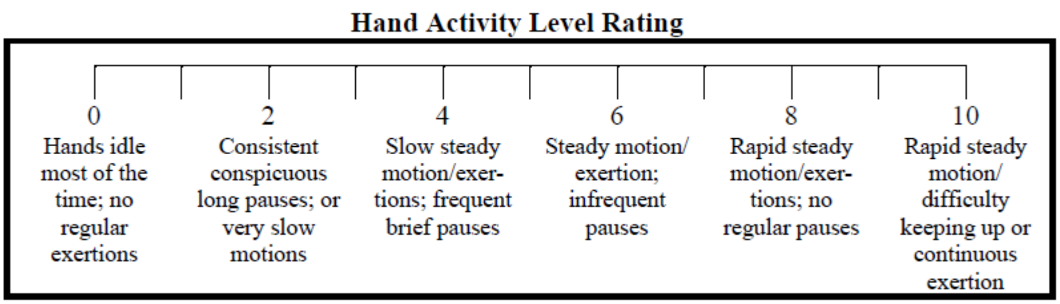


Figure 4-4 Hand Activity Level (HAL) Scale

American Conference of Governmental Industrial Hygienists (ACGIH, 2001) combines another variable, Normalized Peak Force (NPF) with HAL, using the formula: HAL Ratio= Normalized Peak Force/ (10-HAL). A Normalized Peak Force (NPF) is the maximum hand force required for the task, normalized on a scale of 0 to 10. We used the Moore-Garg observational scale (obtained from Bernard, T.E., and ACGIH, 2002) to assess NPF. ACGIH suggests that the ratio NPF / (10-HAL) has a threshold limit value (TLV) of 0.78.

Two researchers analyzed the task videos, and assigned a HAL value and an NPF value for each task. Thus HAL ratio for each task was obtained. The maximum of the two HAL ratios were taken as an indicator of repetitive strain. The raters not only watched the task videos, but were also physically present during data collection, so they had a particularly clear idea about how each task was performed. Average of these maximum HAL ratios across all subjects was taken as indicative of the strain of the task.

4.3.3 Rapid Upper Limb Assessment (RULA)

Rapid Upper Limb Assessment is a method for analyzing upper limb postures to assess the risk of musculoskeletal disorders. It is an easy-to-use stepwise guide to arrive at a score or index that indicates how stressful the posture is.

Three scoring tables and general diagrams of body postures are used to derive a score of exposure to risk factors. Figure 4-5 gives an overview of the stepwise process. The procedure involves assessing postures of two sets of body parts: A. Upper arm, lower arm, wrist, and B. Neck, trunk and legs. For all of these parts, the movement, or observed range of motion is given a number. The numbering protocol is such that 1 means the range of motion is not stressful (i.e., risk factors are minimal). Higher numbers are allocated to body parts with greater range of motion, where observed motion is considered to possess more risk of loading on the body part. . The method provides easy and logical sequence of numbering.

For example, Upper arm scores are:

1 for 20^{o} extension to 20^{o} of flexion

2 for extension greater than 20^{o} or 20^{o} to 45^{o} of flexion

3 for 45^{o} to 90^{o} of flexion, etc.

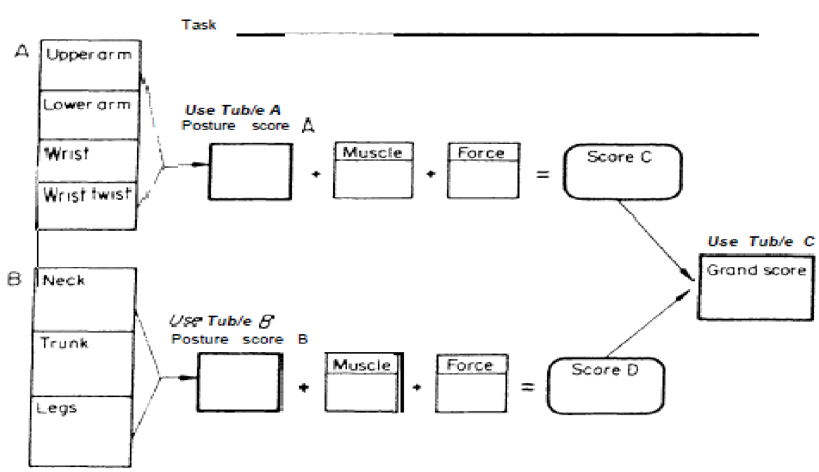


Figure 4-5 RULA scoring scheme (MacAtamney et al.,1993)

Scores for lower arm, wrist, wrist twist, neck, trunk and leg also resembles the scoring scheme shown above. Posture scores from body parts A and parts B are derived. Two other scores concerning muscle load and forces are obtained using tables. These are added to scores from part A and B to obtain scores C and D (Figure 4-4). With these two scores, another table can be used to derive the final score of the posture.

Validity of posture ratings is better for a two-analyst system (Ebersole et al., 2006). Therefore, two researchers assigned RULA scores for the tasks studied. For each task, the video frames where the posture seemed to be most stressful were paused. For these frames, RULA scores were assigned by two researchers. The maximum RULA score of these two was taken as an indication of postural strain. These maximum RULA scores were averaged across subjects to obtain a final RULA score for each task.

4.4 Variables and Their Relationships

Referring to Figure 4-1 Variables obtained from each task, for a single task performed by a single subject, we will have two types of variables:

Measured Variables: These are the variables directly collected from the tasks. There were 42 kinematic measures (7 joint-motions X 3 kinematic measures X 2 types of averages), and 4 EMG variables (2 Muscles X 2 EMG measures). Finger strike rates (in strikes /second) were also calculated visually for each subject and task.

Postural Assessment Scores: These are the variables not determined directly from the task, but by assessing the task postures in a subjective manner. We will have two measures of ergonomic postural strain: HAL ratio and RULA score.

Through statistical analysis, we tried to obtain the association between the measured variables and assessment scores. We considered each measured variable as a dependent variable and corresponding HAL ratio and RULA scores as the independent variables. We expected that HAL ratio and RULA scores would associate with the kinematic and EMG variables monotonically. For example, RULA score may be higher for higher measures of EMG. So, our analysis included correlation analysis.

Since we had a relatively small sample size and we were unsure about their population distribution and variance, we have used a non-parametric correlation coefficient to indicate how closely two variables are associated. We considered that Spearman's coefficient would be appropriate for this analysis.

Spearman rank-order correlation is based on the ranks of the data values (Siegel and Castellan, 1988). The formula used in Statistical Analysis software was:

$$\theta = \frac{\sum_i ((R_i - \bar{R})(S_i - }{\sqrt{\sum_i (R_i - \bar{R})^2 \sum(S_i}}$$

Here R_i is the rank of x_i, S_i is the rank of y_i , $\bar{R}$ is the mean of the R_i values, and $\bar{S}$ is the mean of the S_i values (support.sas.com, 2014).

Chapter 5

Results and Discussions

In this chapter, we present the results of our study. Specifically, we are interested in presenting and comparing different measures of hand strain (kinematic, EMG muscle activity and biomechanical measures) for the three kinds of media activities we studied. A total of 49 measures of strain were computed for each task. In this section, we discuss, based on these measures, the strains involved in the operation of different hand-held devices. We will compare the measures by joint location, muscle EMG activity, and task sub-types. We will also interpret the results from practical product design and ergonomics perspectives.

The focus of our kinematic measurement was on five joints of the thumb and the index finger. These fingers are generally denoted by digits 1 and 2. The metacarpophalangeal (MCP) joints of both these fingers went through two kinds of motion: flexion-extension, and abduction-adduction. We have provided the definitions of these motions in the previous chapter. The distal and proximal interphalangeal (DIP and PIP) joints of the fingers went through only flexion-extension motion. Figure 5-1 shows the locations of the joints and the motions studied.

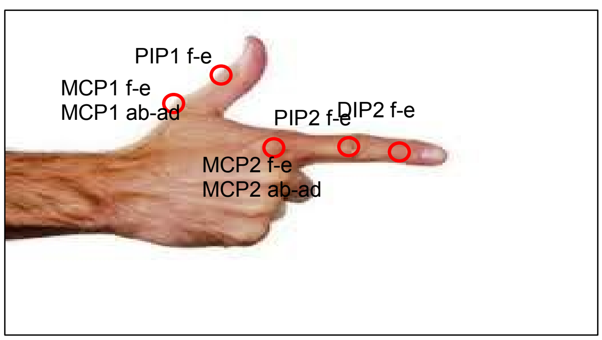


Figure 5-1 Location and abbreviation of joint-motions studied

For ease of our discussions, we have denoted these joints and motions as “MCP1 f-e” (flexion-extension of the metacarpophalangeal joint of the thumb), “MCP1 ab-ad” (abduction-adduction of the metacarpophalangeal joint of the thumb), “PIP1 f-e” (flexion-extension of the interphalangeal joint of the thumb), as “MCP2 f-e” (flexion-extension of the metacarpophalangeal joint of the index finger), “MCP2 ab-ad” (abduction-adduction of the metacarpophalangeal joint of the index finger), “PIP2 f-e” (flexion-extension of the proximal interphalangeal joint of the index finger), and “DIP2 f-e” (flexion-extension of the distal interphalangeal joint of the index finger). Thus, we have obtained joint angles, velocities, and accelerations for seven joint-motions.

When a subject performed a task, angles (measured in degrees), velocities (measured in degrees/s) and accelerations (measured in degrees/s^2) at all seven joints were recorded (and later, computed) in a frame- by- frame manner. For each subject and task, we took the average joint kinematics (angle/velocity/ acceleration) over all the frames, and then averaged that across subjects. This gave us the “average angles”, “average velocities” and “average accelerations”, at all the joints, for any task. Similarly, for any task performed by a subject, we took the maximum joint kinematics (angle/velocity/ acceleration) over all the frames; and then averaged that across subjects. This gave us the “average maximum angles”, “average maximum velocities” and “average maximum accelerations” at all the joints for any task. Thus, for each joint, we had three average and three average maximum measures of kinematics. Considering all the seven joints, we had 42 measures of kinematics. In addition to that, we had four EMG variables, as described in previous chapter, and three measures of postural (ergonomic) strain, giving us a total of 49 measures of strain.

In this chapter, we first provide the task-wise description of hand strain. The operation of devices performed in this study can be divided into three broad categories: gaming tasks, texting tasks, and browsing tasks. Each of these was performed in two variations of techniques. First, we will present a broad kinematic description of these tasks. Then we will dive into comparison, relevance and equivalence of kinematics, location of strain, and task techniques.

5.1. Gaming Tasks

The kinematic, electromyography and postural strain variables for gaming tasks (sequential and natural) are presented in Table 5-1. Although overall averages were more descriptive of the tasks, we wanted to include average maximum values to indicate the maximum strain that occurred at a joint during the course of the task.

Table 5-1 Measures of strain for gaming tasks

Measures of Strain	Location on body	Sequential Gaming	Natural Gaming
Average Angles (Degrees)	MCP 1 f-e	13.97	10.87
	MCP 1 ab-ad	21.38	19.85
	PIP 1 f-e	17.56	16.91
	MCP 2 f-e	16.35	13.75
	MCP 2 ab-ad	8.69	11.2
	PIP 2 f-e	27.25	41.61
	DIP 2 f-e	13.3	19.28
Average Velocities (Degrees/s)	MCP 1 f-e	16.68	13.01
	MCP 1 ab-ad	12.2	11.28
	PIP 1 f-e	21.25	24.96
	MCP 2 f-e	8.13	11.81
	MCP 2 ab-ad	7.63	10.44
	PIP 2 f-e	10.26	15.95
	DIP 2 f-e	13.77	14.75
Average Accelerations (Degrees/s^2)	MCP 1 f-e	210.34	192.27
	MCP 1 ab-ad	147.95	153.4
	PIP 1 f-e	255.86	404.42
	MCP 2 f-e	115.99	180.07
	MCP 2 ab-ad	98.09	138.61
	PIP 2 f-e	139.14	270.8
	DIP 2 f-e	172.71	230.4
Average Maximum Angles (Degrees)	MCP 1 f-e	65.71	22.83
	MCP 1 ab-ad	43.35	29.33
	PIP 1 f-e	40.59	32.28
	MCP 2 f-e	30.71	24.48
	MCP 2 ab-ad	20.14	19.69
	PIP 2 f-e	89.08	53.48
	DIP 2 f-e	45.53	53.78

Table 5-1. Continued

Average Maximum Velocities (Degrees/s)	MCP 1 f-e	160.19	106.8
	MCP 1 ab-ad	123.37	122.45
	PIP 1 f-e	161.92	271.56
	MCP 2 f-e	140.32	116.52
	MCP 2 ab-ad	78.5	113.97
	PIP 2 f-e	111.12	214.55
	DIP 2 f-e	460.94	178.15
Average Maximum Accelerations (Degrees/s^2)	MCP 1 f-e	2905.05	2177.98
	MCP 1 ab-ad	2447.48	2093.67
	PIP 1 f-e	2818.36	4976.26
	MCP 2 f-e	3031.58	2665.01
	MCP 2 ab-ad	1510.17	2352.55
	PIP 2 f-e	2412.38	4054.71
	DIP 2 f-e	8196.38	5463.9
EMG Average Burst Activity (mV)	First Dorsal Interosseous	401.23	676.28
EMG Burst to Average Ratio	First Dorsal Interosseous	1.49	1.37
EMG Average Burst Activity (mV)	Extensor Digitorum	844.14	1392.26
EMG Burst to Average Ratio	Extensor Digitorum	1.92	1.79
Average Strike Rate (Strikes/s)	Fingertip	2.65	4.5
Average Maximum HAL TLV	Posture	0.36	1.4
Average Maximum RULA	Posture	3	3.2

The EMG variables presented in the table include EMG average burst activity and burst to average ratio at two muscles. The postural task strains were measured in terms of average strike rate, average maximum HAL TLV, and RULA values.

5.1.1 Kinematics across joint locations

The overall average and average maximum values of the kinematic variables for two task variations across seven joint locations are shown in Figure 5-2. The solid bars represent natural gaming task, and patterned bars represent sequential gaming task.

Both the overall and maximal average angular displacements were higher for PIP 2 flexion– extension than for any other joint (27.25^{o} and 41.61^{o}). This joint motion is required for pressing buttons as well as holding the device in hand. PIP2 flexion-extension contributes mostly to the operation of the side buttons of the gaming console. Three of the seven joints that were under investigation generated the higher levels of velocities and accelerations – the PIP1, PIP2 and DIP2, all for flexion-extension motions, with the PIP1 dominating the rest for average velocities and accelerations. These joints also generated greater overall and maximal velocities and accelerations, with the PIP1and DIP2 being dominant for the maximal accelerations.

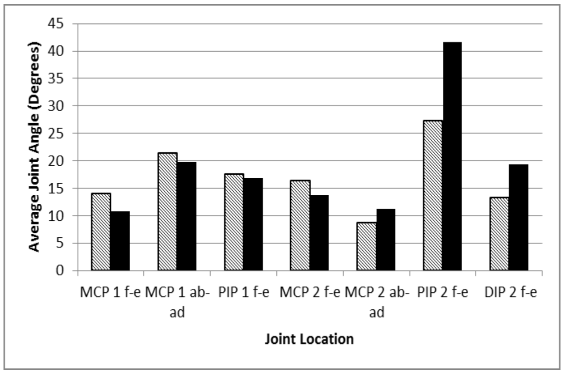
This indicates that the velocities were achieved or changed more rapidly at these joints than the others. The DIP2 joint is nearest to the tip of the index finger, and aids the fingertip to tap the buttons. The natural gaming situation demanded vigorous pressing of the side buttons; hence accelerations may have been higher at interphalangeal joints of the index finger. These effects were not, however, the same across the two different tasks.

While the natural gaming tasks showed greater overall average velocities and accelerations for most joints, especially the PIP1 flexion-extension, the DIP2 joint showed much greater maximal velocities for the sequential gaming. Over the course of the sequential gaming task, there were two particular occasions when the side-buttons were pressed in conjunction with a top-button. Taking the whole task into account, these operations may have resulted in higher maximal velocity at the DIP2 joint; but not a high average velocity. Although PIP2 joint achieved greater angular displacement, it was moved at relatively low velocity and acceleration compared to PIP1 and DIP2 joints.

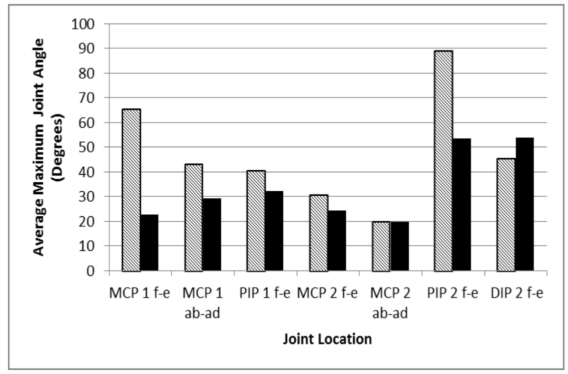
Finger motions occurred at higher average velocity for both the tasks at PIP1 flexion extension although the DIP2 joint attained, on average, a higher maximum velocity than all other joints during natural gaming task.

In general, very high joint accelerations were achieved for gaming tasks. This implies that the joint velocities were attained and/or changed very rapidly. Average accelerations were higher for PIP1 joint flexion-extension in both task variations. This factor probably attributed to the higher average velocity of movement at that joint. In most of the cases, joints where there was higher angular velocity (average or average maximum), corresponding accelerations (average or average maximum) were also higher. Except for the case of DIP joint of index finger (sequential gaming), which achieved very high maximum velocity on average, average maximum acceleration was only moderately high. Joints that achieved, on average, higher maximum accelerations were MCP1 (flexion-extension), PIP1 and PIP2 joints.

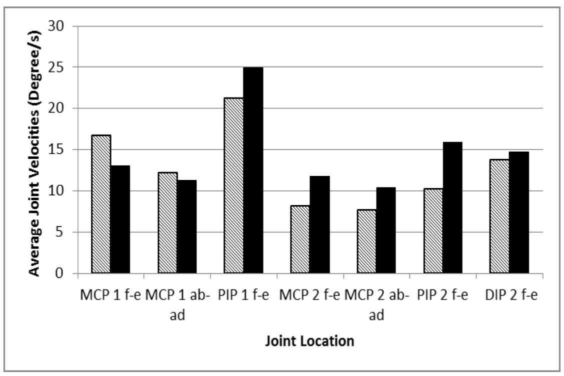
There were obvious differences in kinematics of fingers for the two kinds of gaming task, which will be discussed in a latter section. In general, flexion-extension motion or button pressing was entailed to higher angular displacement, velocities and acceleration. Buttons were pressed at a fiercely high speed. Strike rates, discussed later, will give a better idea in this regard. Abduction adduction motion, required mostly for gaming console joystick and side button operations, was relatively less strenuous in terms of angular motion.



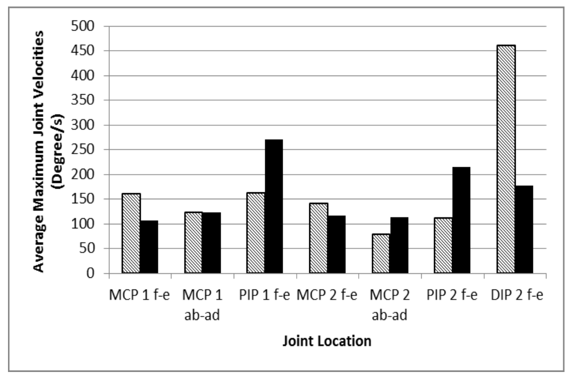
a. Average joint angles (Degrees)



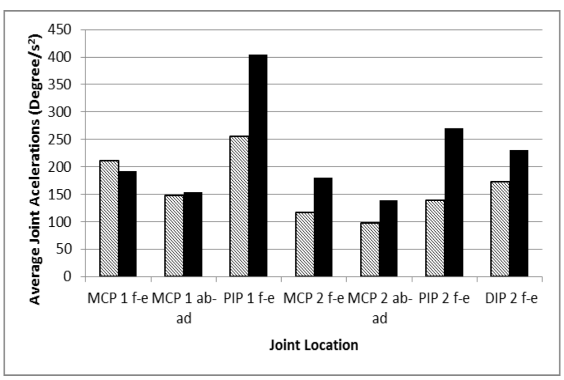
d. Average maximum joint angles (Degrees)



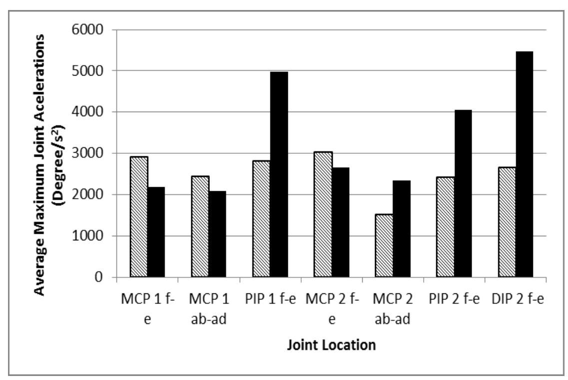
b. Average joint velocities (Degrees/s)



e. Average maximum joint velocities (Degrees/s)



c. Average joint accelerations (Degrees/s^2)



f. Average maximum joint accelerations (Degrees/s^2)

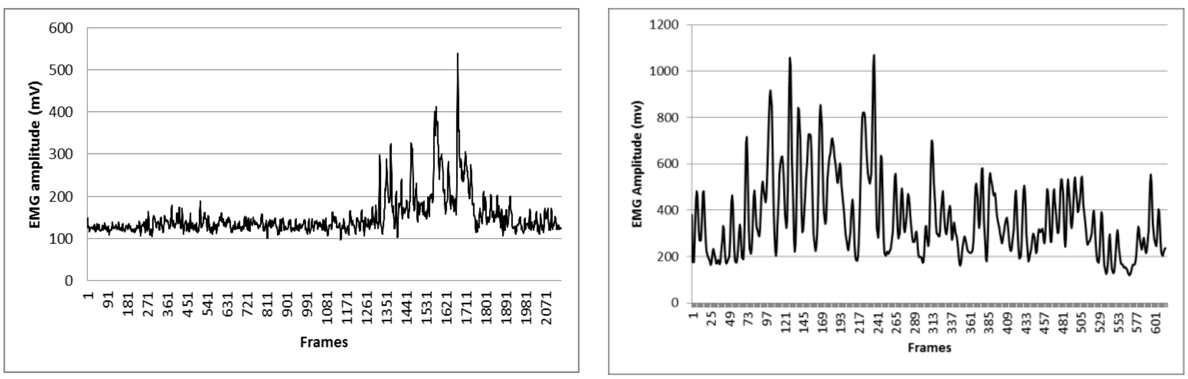
Natural Gaming

Sequential Gaming

Figure 5-2 Average and maximum joint kinematics for gaming tasks

5.1.2 EMG Muscle Activities

For the sequential gaming task, a burst of muscle activity was found in most of the cases near the end of the activity, usually around 65-80% of the completion time. This was the case for both the FDI (First Dorsal Interosseous) and ED (Extensor Digitorum) muscles. For the natural gaming task, the burst patterns were not consistent, and many bursts were found in the same activity. This was a task performed at will; so the patterns were not steady across subjectsFigure 5-3 shows a typical EMG pattern (filtered, rectified) for sequential gaming and a sample EMG pattern for natural gaming.



a. Sequential Gaming

b. Natural Gaming

Figure 5-3 EMG patterns for a subject's ED muscle for gaming activity

For the FDI muscle, higher average burst activity was achieved in natural gaming, but the ratio of burst to average overall activity was higher for sequential gaming. This makes sense because during sequential gaming, the first few movements were slow, and most of the participants performed the task cautiously. Towards the end of the task, there was side button and joystick movement, which needed significant abduction adduction of fingers, triggering FDI muscle activity. Therefore, larger burst-to-average ratio may result.

Similar to FDI muscle, ED muscle also exhibited greater average burst activity for natural gaming, albeit EMG burst-to-average ratio was higher for sequential gaming. This is mainly due to the fact that, in natural setting, the gaming task was performed at will, and buttons were vigorously pressed at higher strike rate. Therefore, both the muscles were used more for natural gaming.

For both the gaming tasks, ED muscle showed higher average burst activity, which indicates higher flexion extension activity, particularly, extension of the proximal phalanges of the index finger. This is in unison with our findings from joint kinematics.

5.1.3 Postural Strain

Average strike rate for the sequential gaming task (2.65) was much lower than that for the random gaming task (4.5). The sequential gaming task was a standardized task where the participants were instructed to perform the game in a sequential order (Press buttons in a predefined schedule). The participants were observed to be cautious in pressing buttons, and compared to real life situations, finger movements were relatively slow. A lower strike rate also indicates smaller muscle efforts (EMG muscle activities also confirm that). Higher strike rates were attained while performing the game in a natural manner, when the participants were instructed to play as if they would play at home and winning was the objective. EMG muscle activities were also higher for this gaming regimen.

Average maximum HAL TLV for the two task techniques were 0.36 and 1.4. Again, natural gaming technique resulted in higher postural score. According to ACGIH, an activity for which HAL TLV exceeds a value of 0.78 is stressful for hand and needs design interventions. Therefore, gaming task is fairly strenuous for fingers, and the issue needs to be addressed with ergonomic interventions.

RULA scores for gaming tasks were 3 and 3.2, this indicates that the sitting upper body posture adopted during these tasks were not ergonomically stressful. However, a higher RULA score in case of natural gaming technique is indicative of a greater postural effort exerted by the hand.

5.1.4 Comparison of task techniques (Sequential vs. Natural)

Maximum joint displacements were higher on average for sequential gaming techniques (Figure 5-2d), indicating that the magnitude of movement was more. Maximal joint displacements for sequential gaming were greater at 5 out of 7 joints. This may be due to (i) caution in tapping in the sequential gaming, and (ii) the need for faster tapping. We may recall from Figure 5-2 that the larger displacements (PIP-2 and MCP-1 flexion extension and ab-ad) were associated with relatively small velocities and accelerations. Joint velocities and acceleration at all joint locations, for both average and average maximum values, were higher or comparable in case of natural gaming (with the exception of average maximum acceleration of DIP flexion extension of index finger). In reference to Table 5-1 , it can be clearly stated that more muscular, kinematic, and postural effort was expended in natural gaming scenario.

To understand whether or not the means of the variables were different for the two task techniques, t –test was performed. Specifically, we performed two- sample Wilcoxon-Mann-Whitney test (Wilcoxon, 1945; Mann and Whitney, 1947); as our data set was small (10 subjects for each gaming regime), and we were unsure about the normality of the dependent variables. For our 49 measures of strain, 49 t-tests were conducted. Task technique (sequential vs. natural) was the independent variable, and each of the measures of strain, for example, average angle of MCP1 f-e, was the dependent variable. We sum up the p values obtained from the t-tests in Table 5-2.

Table 5-2 Results of t-Tests for Gaming Techniques

Variable	Location	p value	Variable	Location	p value
Average Angle	MCP 1 f/e	0.1365	Average Max Angle	MCP 1 f/e	0.0041*
	MCP 1 ab/ad	0.4549		MCP 1 ab/ad	0.0375*
	PIP 1 f/e	0.3669		PIP 1 f/e	0.1342
	MCP 2 f-e	0.3116		MCP 2 f-e	0.0375*
	MCP 2 ab-ad	0.2854		MCP 2 ab-ad	0.4808
	PIP 2 f-e	0.0129*		PIP 2 f-e	0.0375*
	DIP 2 f-e	0.0606		DIP 2 f-e	0.4808

Table 5-2. Continued

Average Velocity	MCP 1 f/e	0.1537	Average Max Velocity	MCP 1 f/e	0.044*
	MCP 1 ab/ad	0.285		MCP 1 ab/ad	0.4548
	PIP 1 f/e	0.3388		PIP 1 f/e	0.0605
	MCP 2 f-e	0.4549		MCP 2 f-e	0.3115
	MCP 2 ab-ad	0.3116		MCP 2 ab-ad	0.3668
	PIP 2 f-e	0.2137		PIP 2 f-e	0.2853
	DIP 2 f-e	0.4849		DIP 2 f-e	0.2136

Table 5-2. Continued

Average Acceleration	MCP 1 f/e	0.2603	Average Max Acceleration	MCP 1 f/e	0.0702
	MCP 1 ab/ad	0.3388		MCP 1 ab/ad	0.4251
	PIP 1 f/e	0.454		PIP 1 f/e	0.0702
	MCP 2 f-e	0.1365		MCP 2 f-e	0.1537
	MCP 2 ab-ad	0.5		MCP 2 ab-ad	0.2603
	PIP 2 f-e	0.3957		PIP 2 f-e	0.4549
	DIP 2 f-e	0.4849		DIP 2 f-e	0.4121
EMG and Ergonomics	EMG -FDI	0.0029*			
	EMG Ratio - FDI	0.0243*			
	EMG -ED	0.0521			
	EMG Ratio-ED	0.3388			
	Strike Rate	0.0008*			
	RULA	0.1841			
	HAL TLV	0.0021*			

The p values which are significant at a level of 0.05 are denoted with an asterisk in the table. Out of our 49 measures of strain, only 10 (20.4%) had means that were statistically significantly different across the two task techniques. The kinematic variables that had significantly different means for the two task techniques were: average flexion-extension angle at PIP1 (p=.0196), average maximum flexion extension angle at MCP1 (p=0.0041), average maximum abduction- adduction angle at MCP1 (P= 0.0375), average maximum flexion-extension angle at MCP2 (p=0.0375), average maximum flexion-extension angle at PIP2 (p=0.0375), and average maximum velocity of flexion-extension at MCP1 (p=0.044). EMG average burst activity (p=0.0029) and burst to average ratio (p=0.0243) at FDI muscle were the only EMG variables that were differently affected by the two gaming scenarios. Among the postural variables, Strike rate (p=0.0008) and HAL TLV (p=0.0021) had different means across the two techniques.

We expected that there would be significant and widespread difference in finger kinematics for the two gaming techniques. Surprisingly, the means of joint angles, velocities and accelerations at many of the locations did not differ significantly based on how the game was played. Only the average flexion-extension angle of the PIP joint of the index finger and average maximum angles (both f-e and ab-ad) of the MCP joint of the thumb were differently affected by sequential and natural gaming. We presumed that the higher angles obtained at the PIP joint of the index finger was due to the posture of the finger. Our t test results clearly indicate that on average, in sequential gaming situation, this joint must have assumed a higher flexion-extension angle either due to posture or cautious activity. It may be due to the fact that the side buttons of the gaming console were used more for the natural gaming task, and index finger was used to operate these buttons. Our results also indicate that on average, the maximum angle attained throughout the task was higher for the sequential gaming task at the thumb MCP joint for both type of motions. A higher maximum velocity of flexion-extension was also achieved at the thumb MCP joint for natural gaming task. In general, this points towards concentrated repetitive activity of the thumb during the sequential gaming task. The fact that EMG activities at FDI muscle were differently affected by gaming techniques supports our observation that natural gaming situation evoked more rapid abduction-adduction of the index finger. Even though the internal joint movement variables were mostly similar or comparable, the natural gaming task appeared a lot more strenuous externally, as indicated by the significantly different mean values of strike rate and HAL TLV.

5.2 Texting tasks

Texting tasks in this study were right- handed single-fingered standardized tasks. Two variations of the task were performed: texting with index finger and with the thumb. The objective was to find out the descriptive measures of strain and to compare the two techniques. Table 5-3 presents the descriptive measures of strain for texting tasks (Index finger texting and thumb texting). Average and average maximum joint angles, velocities and accelerations across five joints of fingers are presented here. Also, average EMG burst activities and burst to average ratio at two pertinent muscles are presented. For postural measures of strain, we present average strike rates, HAL and RULA values for each task. Discussions about the kinematic, EMG, and postural (ergonomics) measures of strain will continue in the following sections, and comparison of the two techniques will be made in light of these measures.

5.2.1 Kinematics across joint locations

For index finger texting, average joint angle was the highest at MCP2 joint flexion-extension, which was more than 30 degrees. Very much comparable to that was the average flexion extension angle of PIP2 joint (around 22 degrees). The flexion-extension motion of the MCP2 and PIP2 contribute to the pressing action of the index finger. A high average angle may indicate that a greater range of joint motion was required for this task; though higher angle of displacement does not necessary mean that a strenuous posture was adopted. Interestingly, the average maximum joint angle was highest at PIP 1 joint flexion extension. This could be due to the nature of index finger texting. Higher PIP 1 flexion extension can be due to the fact that while index finger is being used to do the pressing, the thumb may adopt motions to maintain postural balance, achieving a high angle at any point. However, the average maximum angle at PIP1 flexion- extension (51.27^o) was very much comparable to the average maximum angles achieved for flexion extension of MCP2 (49.54^o) and PIP2 (45.75^o).

Table 5-3 Measures of strain for texting tasks

Measures of Strain	Location on hand	Index texting	Thumb texting
Average Angles (Degrees)	MCP 1 f-e	8.94	6.88
	MCP 1 ab-ad	18.63	26.18
	PIP 1 f-e	13.73	11.68
	MCP 2 f-e	31.84	16.28
	MCP 2 ab-ad	15.79	10.85
	PIP 2 f-e	22.39	28.72
	DIP 2 f-e	6.12	11.87
Average Velocities (Degrees/ s)	MCP 1 f-e	11.04	19.95
	MCP 1 ab-ad	8.98	16.87
	PIP 1 f-e	18.99	43.36
	MCP 2 f-e	25.03	17.24
	MCP 2 ab-ad	15.72	10.88
	PIP 2 f-e	23.36	13.76
	DIP 2 f-e	22.73	18.12
Average Accelerations (Degrees/ s^2)	MCP 1 f-e	160.35	245.17
	MCP 1 ab-ad	109.64	162.76
	PIP 1 f-e	281.5	511.78
	MCP 2 f-e	268.53	221.08
	MCP 2 ab-ad	194.5	143.35
	PIP 2 f-e	292.49	297.93
	DIP 2 f-e	391.7	243.02
Average Maximum Angles (Degrees)	MCP 1 f-e	17.91	21.5
	MCP 1 ab-ad	29.23	39.68
	PIP 1 f-e	51.21	40.09
	MCP 2 f-e	49.54	32.23
	MCP 2 ab-ad	27.24	19.81
	PIP 2 f-e	45.75	70.91
	DIP 2 f-e	22.24	86.58
Average Maximum Velocities (Degrees/ s)	MCP 1 f-e	149.17	118.1
	MCP 1 ab-ad	66.21	113.39
	PIP 1 f-e	267.42	319.11
	MCP 2 f-e	160.58	160.02
	MCP 2 ab-ad	130.99	118.71
	PIP 2 f-e	178.36	258.71
	DIP 2 f-e	255.64	558.95
Average Maximum Accelerations (Degrees/ s^2)	MCP 1 f-e	2600.82	1951.02
	MCP 1 ab-ad	1137.02	1946.38
	PIP 1 f-e	3860.28	5386.15
	MCP 2 f-e	2376.45	2928.45

Table 5-3. Continued

Average Maximum Accelerations (Degrees/ s^2)	MCP 2 ab-ad	1864.08	2114.8
	PIP 2 f-e	3146.73	6318.22
	DIP 2 f-e	4295.06	11485.04
EMG Average Burst Activity (mV)	First Dorsal Interosseous	477.98	333.1
EMG Burst to Average Ratio	First Dorsal Interosseous	1.27	1.24
EMG Average Burst Activity (mV)	Extensor Digitorum	1039.71	512.94
EMG Burst to Average Ratio	Extensor Digitorum	1.53	1.55
Average Strike Rate (Strikes/s)	Fingertip	2.19	2.03
Average Maximum HAL TLV	Posture	0.56	1.07
Average Maximum RULA	Posture	4.2	4.6

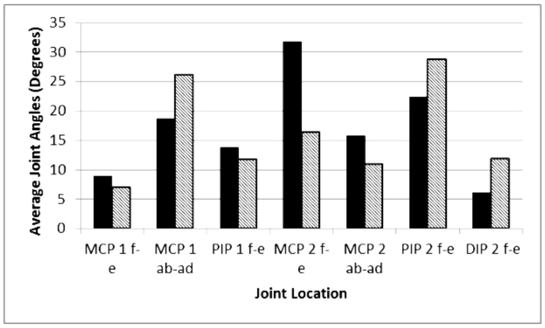
Due to the independent movement of the thumb, average maximum velocities and accelerations also may have been comparably high at the MCP1 joint. Abduction adduction angles of the thumb and index finger were very close, both in case of average and average maximum.

The average joint velocities were higher at all three joints of the index finger for flexion-extension motion. This indicates that the index finger joints moved more rapidly than thumb joints. Average accelerations achieved very high values at index PIP2 and DIP2 joints. Therefore, these joints achieved their velocities at a higher pace.

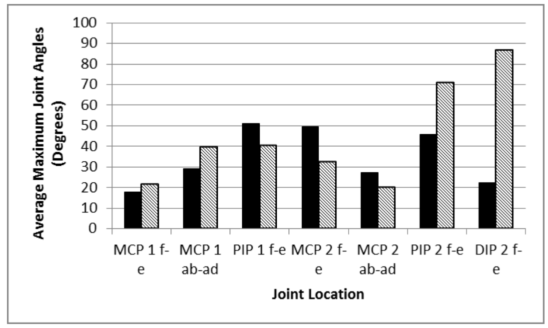
Predictably, similar pattern was found in case of thumb texting (Figure 5-4). Since thumb was doing all the work, MCP and IP joints of the thumb achieved very high average flexion extension angles, velocities, and accelerations. In a comparative study of thumb texting, Gustaffsson et al. (2010) reported that thumb joint median velocities were higher for single-thumb key press techniques, as opposed to two-thumb or medial thumb press techniques. In current study, average velocities at all joints of the thumb and the index finger for thumb texting surpassed those for index finger texting. Studying thumb texting on touchscreen devices, where device type and grip type were the examined variables, Hogg (2010) reported that mean flexion-extension of PIP1 joint was larger (41.29^{o}) than that of MCP 1 (29.13^{o}). Although the task description is completely different, the current study yielded similar comparative results. Average PIP1 f-e angle (11.68^o) was obviously higher than average MCP1 f-e angle (6.88^o) for thumb texting.

Interestingly, we can see that particularly the PIP and DIP joints of the index finger also showed higher angles of displacement. This could be due to the fact the those two joints were used to grip and hold the device in hand, and the angle of motion of the joints varied from subject to subject. Average maximum joint velocity and acceleration were comparably higher at those two joints, too. Although it may seem implausible for these joints to move at high speed while the thumb is doing the work, for some subjects, these joints may have moved, at a fairly high rate, to maintain postural balance while performing the task. In case of index finger texting, it is clear that the flexion-extension motion aided more to the task than abduction adduction motion. Finger abduction adduction was relatively more prominent in case of thumb texting.

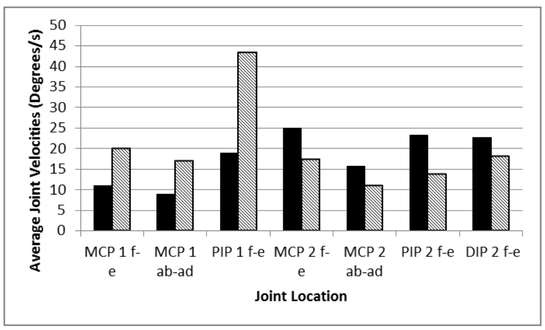
We notice that the average maximum velocities and accelerations at all the joints (except MCP1 f-e) were lower for index finger texting (Figure 5-4 e and f) than thumb texting. While texting was done using the index finger of the dominant hand, the device was held in the non-dominant hand. Therefore the dominant wrist, elbow and shoulder were free to move. In case of many subjects, the wrist and elbow acted as a pivot and dictated the motion of the index finger. Significant flexion and, hence acceleration of the interphalangeal joints was not required. On the other hand, in thumb texting, the device was held in the dominant hand while the thumb of the same hand was used to tap keys. In this case the wrist posture was restricted, and wrist or elbow did not contribute to the motion of the thumb. Thumb flexion and adduction were required for touching the keys, and were the predominant hand motions. Therefore the base of the thumb acted as a pivot and higher maximal acceleration was found at the thumb. Consequently, thumb texting was more strenuous in terms of finger motion.



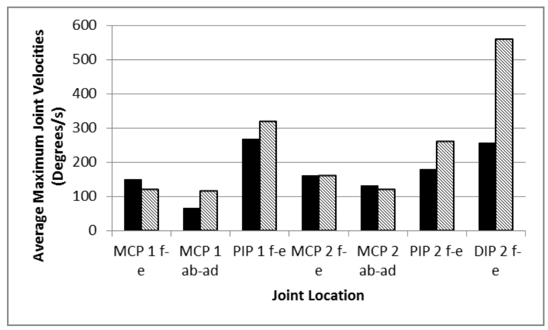
a. Average joint angles (Degrees)



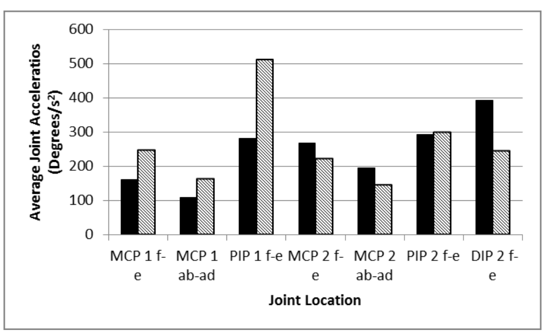
d. Average maximum joint angles (Degrees)



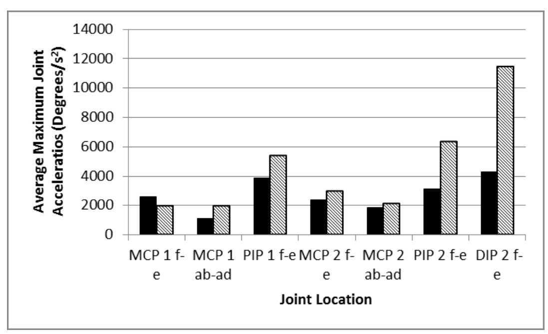
b. Average joint velocities (Degrees/s)



e. Average maximum joint velocities (Degrees/s)



c. Average joint accelerations ($Degrees/s^2$)



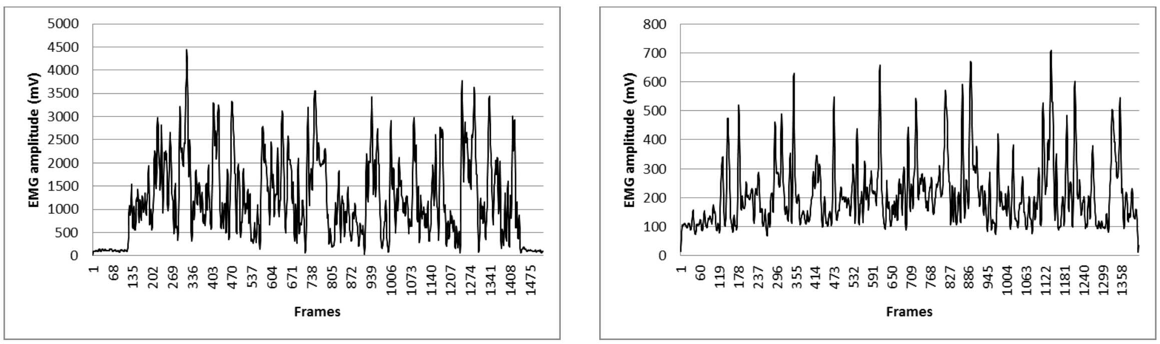
f. Average maximum joint accelerations ($Degrees/s^2$)

Index finger Texting   Thumb Texting

Figure 5-4 Average and maximum joint kinematics for texting tasks

5.2.2 Electromyography Muscle Activities

The EMG activity patterns for texting activities showed very frequent bursts, which in some subjects' cases were not even discernable. The frequent movement of fingers produced very close peaks and valleys. This was in fact one of the reasons we modified Lay et al.'s (2007) approach of EMG burst calculations. Figure 5-5 shows sample EMG activities (filtered and rectified) for a subject's ED muscle while performing the two texting tasks.



a. Index finger texting

b. Thumb texting

Figure 5-5 EMG patterns for a subject's ED muscle for texting activity

For index finger texting, more muscular effort was expended by the extensor digitorum muscle than the first dorsal interosseous muscle. Same was the case for thumb texting. Although exact amount of muscular activity for texting on smartphones was not found in literature, study of texting on mobile phone key pads with one thumb (Gustaffsson et al., 2010), unequivocal with our results, reported higher EMG maximal voluntary activity (5%) for ED muscle than for FDI muscle (4.6%). EMG burst to average ratios were very much similar across the task techniques, and a slightly higher ratio was found for ED muscle. These findings are in unison with the fact that flexion extension of fingers was the prominent motion in both the tasks.

5.2.3 Postural Strain

The average strike rate for index browsing across all the subjects was 2.19 strikes per second. For thumb browsing, it was 2.03 strikes per second. Lower strike rate in case of thumb texting obviously indicates that the technique is more stressful and hinders fast character entry on screen. Average HAL ratio for thumb texting was almost double of that for index texting. HAL ratio basically presents a ratio of how strenuous a task seems (Moore-Garg NPF) and how repetitive the task is (HAL). Higher HAL ratio indicates that the visible effort in thumb texting was a lot higher than the repetitiveness of the task (Proma and Imthan, 2014). Ergonomic posture assessment produced almost similar results for both the texting tasks. RULA values were very close to each other, although thumb texting appeared to be a little more strenuous Since both the tasks were performed sitting down in almost the same posture, the difference in RULA came from the repetitiveness and posture of the wrist. In terms of postural strain, all the indices showed that thumb texting was more strenuous than index texting. Consequently, based on the postural indices, Proma and Imrhan (2014) concluded that using two hands and the dominant index finger is more comfortable and desirable for texting.

5.2.4 Comparison of task techniques (Index finger vs. Thumb)

By sheer values, average angle of displacement was higher at PIP2 joint for index finger texting. However, for thumb texting operation, PIP1 and MCP1 joint abduction-adduction velocities and accelerations were higher. Task-wise, joint velocities and accelerations were also either comparable or higher in case of thumb texting. While more muscular efforts were needed at both the muscles for index finger texting, postural strains in terms of all the postural measures were considerably lower for the task.

Two- sample Wilcoxon-Mann-Whitney t-tests were performed on all the measures of strain (49 variables, 49 t tests) using texting technique (index finger vs. thumb) as the independent variable and the measures of strain as the dependent variables. The results of the t-tests are summed up in Table 5-4 Results of t-test for texting techniques. The significant p values (using α =0.05) are denoted with an asterisk in the table.

Table 5-4 Results of t-test for texting techniques

Variable	Location	p value	Variable	Location	p value
Average Angle	MCP 1 f/e	0.3861	Average Max Angle	MCP 1 f/e	0.1925
	MCP 1 ab/ad	0.5241		MCP 1 ab/ad	0.0280*
	PIP 1 f/e	0.4515		PIP 1 f/e	0.3426
	MCP 2 f-e	0.0161*		MCP 2 f-e	0.0046*
	MCP 2 ab-ad	0.0589		MCP 2 ab-ad	0.0161*
	PIP 2 f-e	0.0914		PIP 2 f-e	0.0465*
	DIP 2 f-e	0.1119		DIP 2 f-e	0.0465*
Average Velocity	MCP 1 f/e	0.0088*	Average Max Velocity	MCP 1 f/e	0.1358
	MCP 1 ab/ad	0.0120*		MCP 1 ab/ad	0.0161*
	PIP 1 f/e	0.0120*		PIP 1 f/e	0.0364*
	MCP 2 f-e	0.0591		MCP 2 f-e	0.4311
	MCP 2 ab-ad	0.1358		MCP 2 ab-ad	0.3862
	PIP 2 f-e	0.0467*		PIP 2 f-e	0.3427
	DIP 2 f-e	0.2622		DIP 2 f-e	0.4769
Average Acceleration	MCP 1 f/e	0.0799	Average Max Acceleration	MCP 1 f/e	0.1122
	MCP 1 ab/ad	0.0626		MCP 1 ab/ad	0.226
	PIP 1 f/e	0.0149*		PIP 1 f/e	0.0364*
	MCP 2 f-e	0.3507		MCP 2 f-e	0.3427
	MCP 2 ab-ad	0.3046		MCP 2 ab-ad	0.5
	PIP 2 f-e	0.5		PIP 2 f-e	0.0591
	DIP 2 f-e	0.3046		DIP 2 f-e	0.1855
EMG and Ergonomics	EMG -FDI	0.0591			
	EMG Ratio - FDI	0.4082			
	EMG -ED	0.0120*			
	EMG Ratio-ED	0.3421			
	Strike Rate	0.2996			
	RULA	0.1485			
	HAL TLV	0.0738			

Out of our 49 measures of strain, there were 15 (30.61%) measures that were differently affected by the two task techniques. Among the kinematic variables, average angle of flexion extension at MCP2 (p= 0.0161), average velocities of flexion extension (p=0.0088) and abduction adduction (p = 0.012) at MCP1 joint, average velocity of flexion extension at PIP1 (p = 0.012) and PIP2 joints (p=0.0467) had different mean values for two texting techniques. Average maximum angles were affected in significantly different ways at five joint locations: abduction-adduction at MCP1 joint (p = 0.028), flexion-extension (p=0.0046) and abduction-adduction (p=0.0161) at MCP2 joint, and flexion-extension of the PIP2 (p=0.0465) as well as DIP2 joints (p=0.0465). Average maximum joint velocities for MCP 1 abduction-adduction (p=0.0161) and PIP 1 flexion extension (p=0.0364) also had statistically significant different means for index and thumb texting techniques. Average acceleration (p=0.0149) and average maximum acceleration (p=0.0364) of flexion-extension at PIP1 were also different across techniques. EMG average burst activity at ED muscle (p=0.0120) was the only EMG variable with significantly different means across the two task techniques. The postural variables had similar means for both index and thumb texting techniques (no significant p value).

Texting involved moving the fingers around the key board to access all the letters. For thumb texting, this involved a lot of abduction-adduction. The fact that the mean velocities (average and maximum) of thumb abduction-adduction as well as flexion—extensions were significantly higher in thumb texting, clearly shows that this technique involved high velocity joint motion of the thumb. In support of this fact, we find that the acceleration of flexion extension (both average and maximum) was significantly higher for thumb texting at the PIP1 joint. Statistically significant differences at the index finger mainly occurred for joint angles (avg max).Significantly higher means of flexion extension angles at PIP2 and DIP2 joints occurred during thumb texting. This may have happened because of the posture adopted by the index finger in holding the device.

Overall, thumb texting was found to be more stressful than index finger texting. When the other fingers are used to hold the device, movement of the thumb is restricted. The thenar eminence is placed against the device to hold it in position. The same muscles that are used for flexion-extension of the fingers are then being used to grip and hold the device in place. It is also possible that more effort goes into reaching far-away characters on the keyboard, taking more time to press a character.

5.3 Browsing or Swiping Tasks

Most browsing tasks are performed by swiping a single finger over the touch screen of the device. Mostly the tip of the thumb or index finger and in some cases the middle finger is used. In this study, two variations of swiping task were explored: browsing with index finger and browsing with the thumb. The objectives were, firstly, to provide a kinematic description of single fingered swiping tasks on smartphone in terms of angular movement, velocity, and acceleration; and secondly, to make a comparative evaluation between the use of thumb versus the index finger for the same task so that a preferred posture can be suggested.

Table 5-4 provides the descriptive values of the measures of strain. As before, average and average maximum joint angles, velocities, and accelerations at index and thumb finger joints are presented along with average EMG burst activities, burst to average ratio at two pertinent muscles, and the postural measures of strain: strike rates, HAL and RULA values for each task.

5.3.1 Kinematics across joint locations

Joint angles, velocities and accelerations were compared based on the average and the average maximum joint angles achieved throughout the tasks across subjects. Table 5-5 and Figure 5-6 shows these measures at each joint for the two techniques.

On average, the highest angle was achieved during index finger browsing at the base of the index finger for flexion-extension motion (MCP2 f-e). PIP joint of the index finger also went through considerable angular motion during index finger browsing.

Table 5-5 Measures of strain for browsing tasks

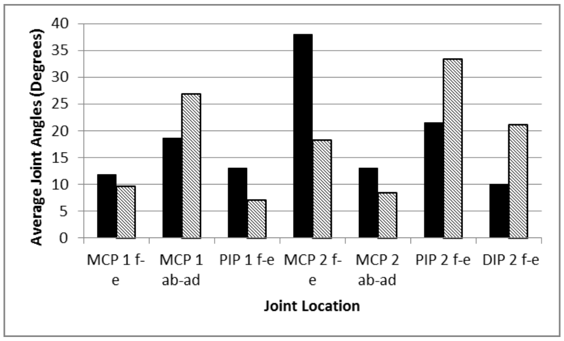
Measures of Strain	Location on hand	Index Browsing	Thumb Browsing
Average Angles (Degrees)	MCP 1 f-e	11.76	9.66
	MCP 1 ab-ad	18.57	26.89
	PIP 1 f-e	13.05	7
	MCP 2 f-e	37.96	18.23
	MCP 2 ab-ad	13.03	8.36
	PIP 2 f-e	21.42	33.39
	DIP 2 f-e	10.03	21.07
Average Velocities (Degrees/ s)	MCP 1 f-e	23.28	68.42
	MCP 1 ab-ad	19.14	35.33
	PIP 1 f-e	39.84	48.02
	MCP 2 f-e	37.1	13.94
	MCP 2 ab-ad	25.22	14.8
	PIP 2 f-e	29.01	10.21
	DIP 2 f-e	39.51	18.01
Average Accelerations (Degrees/ s^2)	MCP 1 f-e	312.24	1086.38
	MCP 1 ab-ad	206.43	598.61
	MCP 2 f-e	481.42	211.5
	MCP 2 ab-ad	402.33	241.31
	PIP 2 f-e	376.29	296.9
	DIP 2 f-e	649.41	197.34
Average Maximum Angles (Degrees)	MCP 1 f-e	33.53	15.33
	MCP 1 ab-ad	48.59	33.15
	PIP 1 f-e	42.55	11.9
	MCP 2 f-e	87.5	20.32
	MCP 2 ab-ad	33.54	10.7
	PIP 2 f-e	52.85	35.69
	DIP 2 f-e	32.24	31.68
Average Maximum Velocities (Degrees/ s)	MCP 1 f-e	46.64	121.91
	MCP 1 ab-ad	38.06	63.98
	PIP 1 f-e	64.87	91.52
	MCP 2 f-e	65.57	31.35
	MCP 2 ab-ad	51.11	31.21
	PIP 2 f-e	58.73	25.12
	DIP 2 f-e	73.51	41.03
Average Maximum Accelerations (Degrees/ s^2)	MCP 1 f-e	640.69	2012.1
	MCP 1 ab-ad	418.82	1064.83
	PIP 1 f-e	1239.54	1574.39
	MCP 2 f-e	1012.26	524.71

Table 5-5. Continued.

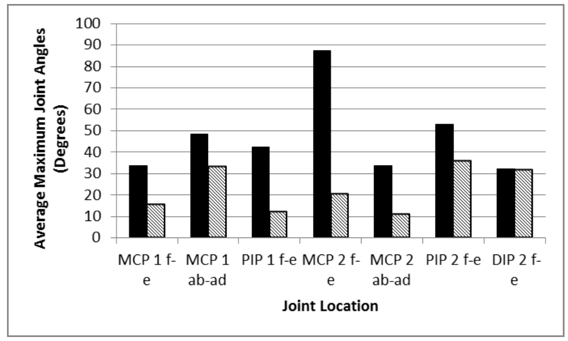
	MCP 2 ab-ad	823.13	574.46
	PIP 2 f-e	884.82	716.27
	DIP 2 f-e	1249.78	594.28
EMG Average Burst Activity (mV)	First Dorsal Interosseous	405.93	225.91
EMG Burst to Average Ratio	First Dorsal Interosseous	1.26	1.41
EMG Average Burst Activity (mV)	Extensor Digitorum	594.81	326.37
EMG Burst to Average Ratio	Extensor Digitorum	1.65	1.77
Average Strike Rate (Strikes/s)	Fingers	2.54	2.09
Average Maximum HAL	Posture	0.21	0.32
Average Maximum RULA	Posture	4	3.8

The angular velocities were higher at MCP2 and PIP2 joints for flexion-extension motion. Maximum velocity throughout the task was achieved at the DIP2 joint, which was quite comparable to the velocities at the PIP2 joint and MCP2 joint for flexion-extension. At all the joints of the index finger, higher accelerations were found. Interestingly, there was considerable angular velocity and acceleration at the PIP joint of the thumb as well. Similar to texting, this phenomenon may be attributed to the involuntary uncontrollable movement of the thumb along with the index finger, which was observed in case of some subjects.

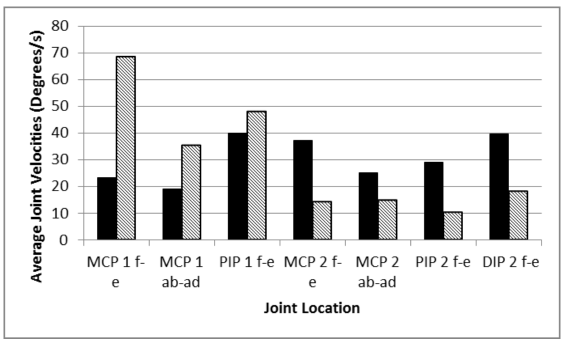
As expected, the thumb joint motions were prominent during thumb browsing. MCP1 joint went through very high angular displacement, on average, while abduction adduction of the thumb took place.



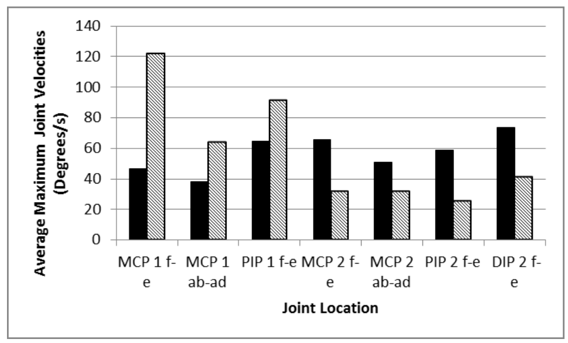
a. Average joint angles (Degrees)



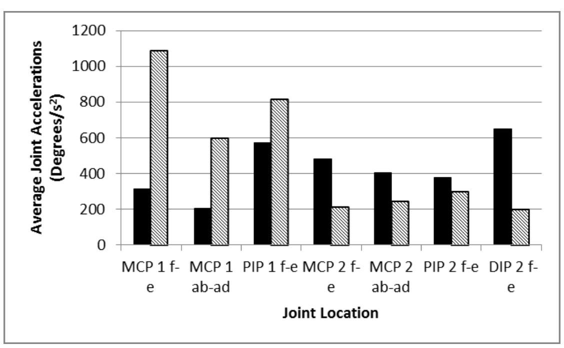
d. Average maximum joint angles (Degrees)



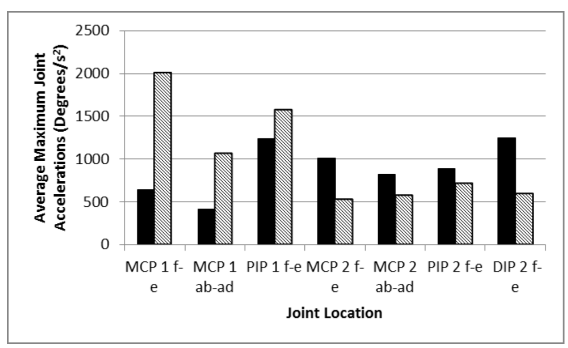
b. Average joint velocities (Degrees/s)



e. Average maximum joint velocities (Degrees/s)



c. Average joint accelerations (Degrees/s^2)



f. Average maximum joint accelerations (Degrees/s^2)

Index finger Browsing   Thumb Browsing

Figure 5-6 Average and maximum joint kinematics for browsing tasks

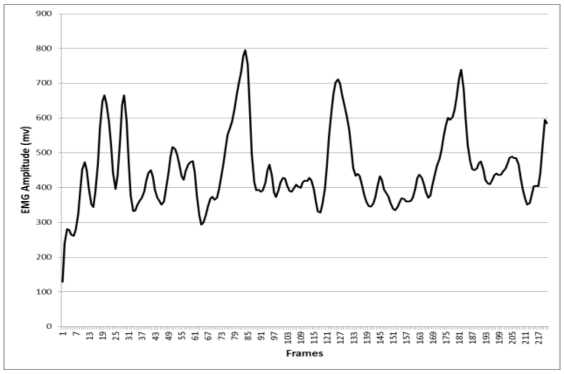
Surprisingly, very high angular displacement of PIP2 and DIP2 joint also occurred, which can be attributed to the holding of the device. The velocities and accelerations at these joints, however, were minimal. This suggests that these joints did not go through much motion during the activity. This is plausible that, as the index finger of the hand was used to hold and support the phone during the activity, while the thumb performed the swiping task across the screen.

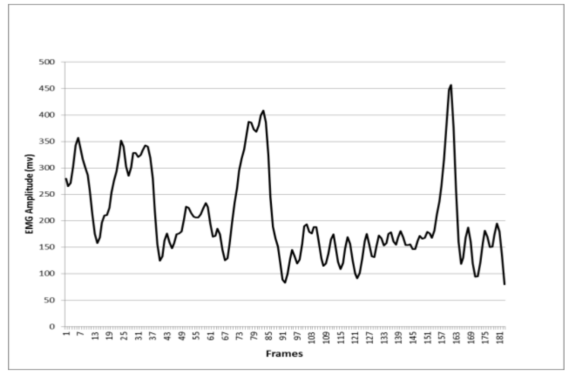
Joint velocities and accelerations at the thumb joints were prominent during thumb browsing, and the values were comparable. Thumb flexion-extension at the MCP1 joint occurred at maximum velocity and acceleration. Maximum velocities and accelerations of PIP1 joint were also very high. Thumb abduction adduction at MCP1 joint also occurred at a relatively high velocity and acceleration.

While in texting, we found that flexion extension aided the task most, the same cannot be said for the browsing or swiping activity. Abduction adduction of fingers was of comparable importance, if not equal.

5.3.2 EMG Muscle Activities

The task of browsing was a relatively short one. The participants were asked to swipe across the screen three times and end with a press as if they were checking emails. As a result, the EMG patterns showed four bursts across the task timeline. Since the subjects performed the task at their own pace, the bursts were not similarly spaced across the subjects. Figure 5-7shows a sample EMG pattern of a subject's ED muscle while performing both variations of the task.





a. Index browsing   b. Thumb browsing

Figure 5-7 EMG patterns for a subject's ED muscle for browsing activity

In both variations of the task, ED muscle went through more activity than FDI muscle, but the amounts were somewhat comparable. This confirms our findings from kinematics. Both flexion extension and abduction adduction of fingers were important for this task, although a little higher amount of flexion extension occurred. Although the sheer values of average burst activity were higher in index browsing, EMG burst to average ratio was higher for thumb browsing.

5.3.3 Postural Strain

Strike rates were higher for index finger browsing, indicating that it was easier to swipe across the screen with the index finger when the rest of the dominant hand was free. In case of thumb browsing, the fingers except for the thumb were engaged in holding the device, restricting the motion of the thumb to an extent. The HAL ratio was also higher in case of thumb browsing, indicating exertion a higher visible effort. Since the task was a sedentary one, postural assessment or RULA values were very close for both the tasks. But overall, from postural perspective, thumb browsing appeared to be more strenuous.

5.3.4 Comparison of task techniques (Index finger vs. Thumb)

Overall, Index finger browsing showed very high average angle for MCP 2 flexion-extension. But average velocities and accelerations at thumb joints were a lot higher for thumb texting activity. EMG activities were comparable for both the techniques; although compared to the average muscle activity, higher burst activity was achieved for thumb texting. From postural perspective, all the indices were somewhat higher for thumb browsing, which indicates that a greater visible postural effort was expended for the task.

As before, Wilcoxon-Mann-Whitney rank-sum t-tests were performed on all the measures of strain (49 variables, 49 t tests). Browsing technique (index finger vs. thumb) was the independent variable and each of the measures of strain was the dependent variable. The p values obtained from the t tests are showed in Table 5-6. The significant p values (using α =0.05) are denoted with an asterisk.

Table 5-6 Results of t-test for browsing techniques

Variable	Location	p value	Variable	Location	p value
Average Angle	MCP 1 f/e	0.5	Average Max Angle	MCP 1 f/e	0.0184*
	MCP 1 ab/ad	0.0473*		MCP 1 ab/ad	0.0473*
	PIP 1 f/e	0.0718		PIP 1 f/e	0.0108*
	MCP 2 f-e	0.0184*		MCP 2 f-e	0.0061*
	MCP 2 ab-ad	0.1054		MCP 2 ab-ad	0.0061*
	PIP 2 f-e	0.0184*		PIP 2 f-e	0.0301*
	DIP 2 f-e	0.2654		DIP 2 f-e	0.1481
Average Velocity	MCP 1 f/e	0.0718	Average Max Velocity	MCP 1 f/e	0.0301*
	MCP 1 ab/ad	0.1481		MCP 1 ab/ad	0.2017
	PIP 1 f/e	0.2017		PIP 1 f/e	0.2017
	MCP 2 f-e	0.0184*		MCP 2 f-e	0.0718
	MCP 2 ab-ad	0.1481		MCP 2 ab-ad	0.1481
	PIP 2 f-e	0.0184*		PIP 2 f-e	0.105
	DIP 2 f-e	0.105		DIP 2 f-e	0.105
Average Acceleration	MCP 1 f/e	0.105	Average Max Acceleration	MCP 1 f/e	0.105
	MCP 1 ab/ad	0.2017		MCP 1 ab/ad	0.2654
	PIP 1 f/e	0.2017		PIP 1 f/e	0.2017
	MCP 2 f-e	0.0718		MCP 2 f-e	0.2017
	MCP 2 ab-ad	0.2654		MCP 2 ab-ad	0.5
	PIP 2 f-e	0.3381		PIP 2 f-e	0.3381
	DIP 2 f-e	0.0301*		DIP 2 f-e	0.1481

Table 5-6. Continued

EMG and Ergonomics	EMG -FDI	0.0473*
	EMG Ratio - FDI	0.3381
	EMG -ED	.0473*
	EMG Ratio-ED	0.2017
	Strike Rate	0.4173
	RULA	0.3669
	HAL TLV	0.5

Fifteen out of our 49 measures of strain (30.61%) demonstrated statistically significant different means across the two browsing techniques. Average angles of abduction -adduction at MCP 1 (p=.0473) joint had different means for the two browsing techniques, so did the average flexion-extension angles of MCP2 (p=0.0184) and PIP2 (p=0.0184). The two types of browsing tasks differently affected average maximum joint angles at six locations: flexion extension (p=0.0184) and abduction adduction (p=0.0473) at MCP 1, flexion- extension of PIP1 (p=0.0108), flexion extension (p=0.0061) and abduction adduction (p=0.0061) at MCP2, and flexion-extension at PIP1 (p=0.0301). Average flexion-extension velocities were significantly different at MCP2 (p=0.0184) and PIP2 (p=0.0184). Average maximum velocity of flexion extension at the MCP 1 joint also showed significantly different means for the two browsing tasks. Average accelerations were significantly different only at DIP2 (p=0.0301). EMG average burst activities at both FDI (p=0.0473) and ED (p=0.0473) muscles showed significant differences across task techniques. None of the postural variables were significantly different.

Mostly the kinematic measures of angles at all the joints differed significantly for thumb and index finger browsing. A higher angle of flexion-extension or abduction- adduction may not necessarily mean that a strenuous posture was adopted. This difference mainly stemmed from the posture of the index finger while holding the device during thumb browsing. While browsing with the index finger, the finger was more in an extended state, and was flexed when needed to press characters. In thumb texting, the index finger adopted a flexed posture in order to grip and hold the device. In case of velocities and accelerations, statistically significant differences were limited. This probably shows that the tasks were more different in posture than in joint motion. The ergonomic task variables did not show significantly different means across the two tasks. The strain of the tasks perceived by an observer was similar for both the tasks. A clear distinction could not be drawn, but overall thumb browsing was, based on the sheer numbers, more stressful than index finger browsing.

5.4 Correlation of Ergonomic, EMG and Kinematic Variables

One of the main objectives of this study was to learn about the relationship between the ergonomic variables and the kinematic and EMG variables. For hand intensive device operation tasks, using tools of ergonomics for postural analysis is very commonly practiced. Obviously, the amount of information acquired from kinematic and EMG variables is a lot more; and it is concrete and credible. On the other hand, ergonomics postural variables such as HAL TLV or RULA are easy to use and do not require complex experimental setups. These methods are vastly based on subjective opinions and observations, which may somewhat differ from person to person; therefore the inferences made are not always impeccable.

The objective of our study was to find a relationship between each of the ergonomics variables (independent variable) and each of the kinematic and EMG variables (dependent variables). Since all the variables in this study were observational (not fixed or controlled), and linearity of relationship was not certain, non-parametric correlation analysis was assumed to be more appropriate for this study. We calculated the Spearman correlation coefficients for each (X_i, HAL_i) and (X_i, $RULA_i$) pairs of variables; where X_i represents a kinematic, EMG or postural variable, and HAL_i and $RULA_i$ are the corresponding HAL TLV and RULA values. There were 48 pairs of variables to study for HAL and RULA (i =48).

5.4.1 Correlation with HAL TLV

Table 5-7 represents the Spearman correlation coefficients (r) between HAL TLV and the other 48 variables. The significant p values (using α=0.05) are marked with an asterisk.

Table 5-7 Spearman Correlation Coefficients between HAL TLV and other variables

Spearman Correlation Coefficients (p values)			
Average Angle	HAL TLV	Max Angle	HAL TLV
MCP1f-e	-0.16519(0.2782)	MCP1f-e	-0.08833(0.5639)
MCP1ab-ad	-0.15602(0.3061)	MCP1ab-ad	-0.236(0.1186)
PIP1f-e	0.35526(0.0166*)	PIP1f-e	0.1371(0.3692)
MCP2f-e	-0.08257(0.5897)	MCP2f-e	-0.15701(0.303)
MCP2ab-ad	0.1886(0.2147)	MCP2ab-ad	0.06791(0.6576)
PIP2f-e	0.07824(0.6094)	PIP2f-e	-0.07756(0.6211)
DIP2f-e	0.03686(0.81)	DIP2f-e	0.13035(0.399)
Average Velocity	HAL TLV	Max Velocity	HAL TLV
MCP1f-e	0.00131(0.9932)	MCP1f-e	0.2671(0.0761)
MCP1ab-ad	0.05759(0.7071)	MCP1ab-ad	0.27999(0.0625)
PIP1f-e	0.1853(0.223)	PIP1f-e	0.45884(0.0015*)
MCP2f-e	0.1694(0.2659)	MCP2f-e	0.26408(0.0796)
MCP2ab-ad	0.15508(0.3091)	MCP2ab-ad	0.2258(0.1358)
PIP2f-e	0.22068(0.1452)	PIP2f-e	0.46557(0.0013*)
DIP2f-e	0.03994(0.7945)	DIP2f-e	0.15571(0.3071)
Average Acceleration	HAL TLV	Max Acceleration	HAL TLV
MCP1f-e	0.07481(0.6253)	MCP1f-e	0.324(0.0299*)
MCP1ab-ad	0.15039(0.3241)	MCP1ab-ad	0.26785(0.0753)
PIP1f-e	0.27391(0.0686)	PIP1f-e	0.50808(0.0004*)
MCP2f-e	0.25879(0.0861)	MCP2f-e	0.29922(0.0459*)
MCP2ab-ad	0.13547(0.3749)	MCP2ab-ad	0.30372(0.0425*)
PIP2f-e	0.37639(0.0108*)	PIP2f-e	0.4486(0.002*)
DIP2f-e	0.09202(0.5524)	DIP2f-e	0.5829(<.0001*)
EMG and Ergonomics	HAL TLV		
EMG FDI	0.15266(0.3168)		
EMG Ratio FDI	-0.01474(0.9234)		
EMD ED	0.28321(0.0594)		
EMG Ratio ED	0.11639(0.4464)		
Strike rate	0.40402(0.0059*)		
RULA	-0.0066(0.9656)		

There was negative correlation between HAL TLV and average and maximum flexion-extension and abduction adduction angles of the thumb MCP joint. Similar was the case with average and average maximum flexion-extension angles index finger MCP joint, and average maximum angle of PIP2 flexion-extension. However, none of the negative correlations were statistically significant (α=0.05). Intuitively, we would expect that a higher angle of flexion-extension or abduction adduction would indicate a stressful posture, and therefore, a positive correlation should exist between HAL TLV and angle of displacement of joints. But clearly, that conclusion could not be drawn. It should be kept in mind that at neutral or least stressful posture, the fingers of the hand are nearly straight, i.e., they adopt greater angles.

We should keep in mind that HAL TLV is a ratio between a subjective rating of the amount of effort or force exerted and the repetitiveness of hand activity. A high HAL TLV value indicates either a higher force exerted to achieve the task or a higher repetitive action of any part of the hand or both. Therefore, the fact that the correlation between angles of movement is not always positive should not be surprising. It may very well be the case that a higher abduction-adduction angle (thumb away from the hand) of the thumb MCP joint may make the activity seem less effortful. We can clearly imagine that when a higher flexion-extension angle of the thumb MCP joint is achieved, the thumb is in a more neutral posture; therefore we would naturally assume that the posture is relatively effortless.

The highest significant positive correlation between HAL TLV and any joint angle was found in case of average flexion extension angles of index finger PIP joint (35.52%, p=0.0166). Although an open index finger or a high angle of motion would appear to be less effortful, we think that in this case, PIP 2 flexion-extension essentially was very much associated with the repetitiveness of the movement. Therefore, on average, high HAL TLV values were assumed for high PIP 2 f-e angles.

Interestingly, HAL TLV was more closely associated with joint velocities and accelerations, particularly with the average maximums. Average maximum velocities at all joints were positively correlated with HAL TLV, with a higher than 15% value, though not all of the correlations were significant. Statistically significant correlation was found with the maximum flexion extension velocities at PIP1 (45.88%, p=0.0015) and PIP2 (46.55%, p=0.0013), where we see similar amount of linear association. This may be attributed to the fact that the visible repetitive effort or pressing of buttons at both the fingers were achieved through these joints. Joint velocities were more representative of the repetitiveness; therefore higher HAL TLV values were more associated with these variables.

Average and maximum accelerations were also highly correlated with HAL TLV. Average maximum acceleration at all joints, except for abduction-adduction of MCP1, were significantly correlated with HAL TLV. Maximum accelerations for flexion-extension of the MCP joints at both the fingers (MCP1f-e=32.4%, p= 0.029; MCP2f-e=29.9%, p=.0459) and also abduction-adduction of the index finger (MCP2 ab-ad=30.37%,p=0.0425) were significantly correlated with HAL TLV. Similar to velocities, average maximum accelerations for flexion –extension of the PIP joints of thumb and index fingers also had very high correlation values (PIP 1 = 50.8%, p= .0004; PIP 2 = 44.9%, p=0.002). The fact that the average maximum that accelerations were more associated with HAL TLV tells us that rapid change of joint velocities projected more visible repetitiveness or postural effort.

An interesting fact to notice in case of accelerations was that the average maximum flexion extension acceleration at the DIP joint of the index finger achieved a very high and significant (58.29%, p<.001) correlation with HAL TLV. This is a bit surprising, and it is the highest correlation value observed of any kinematic variable with HAL TLV. Again, if we imagine how HAL TLV was assigned, a possible explanation may emerge. DIP2 is the nearest joint that is visibly seen when any button is pressed with index finger. Therefore higher acceleration at this joint would mean a steady high increase in velocity (repetitiveness). However, this explanation conflicts with the fact that the maximum average velocity at this joint was not found to be significantly correlated with HAL TLV (r = 15.6%, p=0.3071).

None of the EMG variables showed significant association with HAL TLV. EMG burst to average ratio at FDI muscle was negatively correlated, even though the value was very small and insignificant. Among the postural strain variables, strike rate was significantly correlated with HAL TLV (r = 40.4%, p=0.0059). This makes perfect sense, because higher strike rate would essentially mean higher repetitive effort visible to the observer. Correlation between HAL TLV and RULA, our two ergonomic variables, was extremely small and insignificant (r = 0.6%, p=0.9656); therefore we can safely say that they were uncorrelated.

5.4.2 Correlation with RULA

The other ergonomic or postural variable assigned to tasks in this study was RULA. This was again, a subjective tool, and the numbers were assigned based on upper body posture. In Table 5-8, we present the Spearman correlation coefficients (r) between RULA and the other 48 variables. Any correlation value that is significant at a 0.05 level is marked with an asterisk.

Table 5-8 Spearman Correlation Coefficients between RULA and other variables

Spearman Correlation Coefficients (p values)			
Average Angle	RULA	Average Max Angle	RULA
MCP1f-e	-0.28481(0.0579)	MCP1f-e	-0.16133(0.2897)
MCP1ab-ad	-0.05932(0.6987)	MCP1ab-ad	-0.30552(0.0413*)
PIP1f-e	-0.08948(0.5589)	PIP1f-e	-0.02319(0.8798)
MCP2f-e	0.26199(0.0821)	MCP2f-e	0.11004(0.4718)
MCP2ab-ad	0.07163(0.6401)	MCP2ab-ad	0.40291(0.0061*)
PIP2f-e	-0.28723(0.0557)	PIP2f-e	-0.17695(0.2505)
DIP2f-e	0.00866(0.955)	DIP2f-e	-0.03393(0.829)
Average Velocity	RULA	Average Max Velocity	RULA
MCP1f-e	-0.13121(0.3903)	MCP1f-e	-0.34455(0.0205*)
MCP1ab-ad	0.02793(0.8555)	MCP1ab-ad	0.27237(0.0703)

Table 5-8. Continued

PIP1f-e	-0.12147(0.4267)	PIP1f-e	-0.09128(0.5509)
MCP2f-e	0.31003(0.0382*)	MCP2f-e	0.49684(0.0005*)
MCP2ab-ad	0.41393(0.0047*)	MCP2ab-ad	0.47073(0.0011*)
PIP2f-e	0.27311(0.0695)	PIP2f-e	0.1405(0.3573)
DIP2f-e	0.27269(0.0699)	DIP2f-e	0.08191(0.5927)
Average Acceleration	RULA	Average Max Acceleration	RULA
MCP1f-e	-0.11447(0.454)	MCP1f-e	-0.21479(0.1615)
MCP1ab-ad	0.10895(0.4762)	MCP1ab-ad	0.38963(0.0089*)
PIP1f-e	-0.03291(0.8301)	PIP1f-e	0.02635(0.8652)
MCP2f-e	0.53346(0.0002*)	MCP2f-e	0.69903(<.0001*)
MCP2ab-ad	0.47425(0.001*)	MCP2ab-ad	0.70156(<.0001*)
PIP2f-e	0.20839(0.1695)	PIP2f-e	0.28664(0.0592)
DIP2f-e	0.38548(0.0098*)	DIP2f-e	0.26085(0.0995)
EMG and Ergonomics	RULA		
EMG FDI	-0.28579(0.057)		
EMG Ratio FDI	-0.30158(0.0441*)		
EMD ED	-0.12838(0.4007)		
EMG Ratio ED	-0.22616(0.1352)		
Strike rate	-0.33729(0.0235*)		
HAL	-0.0066(0.9656)		

Although the correlations were not significant in most of the cases, RULA was found to be negatively correlated with many angle, velocity and acceleration variables at different joints. To explain this, we must revisit how RULA values were assigned. RULA values were assigned based on neck, upper arm, lower arm, hands and leg posture and the overall weight handled. Individual finger activities had little to do with RULA. This postural analysis tool yields an amalgamated value of the overall postural effort of the whole upper body, and is not concentrated on hand activity. Probably that is why there are more negative correlations found in case of RULA than in HAL TLV.

In table 5-5, we see that both average and average maximum angles at many joints are negatively correlated with RULA. The explanation here can be similar to the HAL TLV scenario. A higher angle does not necessarily project a higher visible effort. One important fact to notice was that all the significant correlations occurred at the MCP joints of the fingers. Average maximum angle of abduction-adduction at MCP 1 was negatively correlated with RULA (r=-30.5%, p=0.0413), though the velocities at that joint did not correlate with RULA significantly. The average maximum accelerations for abduction-adduction of the same joint was, on the other hand, highly significantly correlated (r = 38.96%, p=0.0089) with RULA. It is difficult to visualize why this may happen. The abduction-adduction of the thumb, at higher angles, would generally mean that the thumb is either extremely close to the other fingers, or extremely away from them. Neither of these postures would appear to be stressful to the eyes of a RULA observer. Rapid increase in velocity of thumb abduction-adduction, on the other hand, may appear more strenuous, as indicated by positive significant correlation. There was significant negative correlation between RULA and average maximum velocity of flexion-extension at MCP1 (r= -34.45%, p = 0.0205), though none of the angles or acceleration at this joint were significantly correlated with RULA. This was a bit vexing, but we would leave this explanation to the fact that not all the aspects of the intrinsic motions of the joints had visible appeal to the observers. The reason may also lie in the fact that RULA considers only the overall posture of the hand and not the repetitiveness of individual fingers. Also, while considering the overall posture of the hands and wrist, the raters may have looked at other parts of the hand with more concentration than the thumb.

Interestingly, all measures of velocities and acceleration, both average and average maximums, at MCP2 joint were significantly and positively correlated with RULA. The average velocities for flexion extension (r = 31%, p=0.0382) and abduction adduction (r= 41.39%, p= 0.0047) of MCP 2 joint significantly correlated with RULA. Similar results were also found for average maximum velocities (MCP 2 f-e = 49.68%, p=0.0005; MCP 2 ab-ad = 47.07%, p= 0.0011). We would say that RULA had about 30-50% positive correlation with velocities of index finger flexion-extension and abduction-adduction. On the other hand, the correlation values of RULA with average and average maximum accelerations at this joint were quite high and significant. The average accelerations of flexion extension and abduction-adduction at MCP 2 were significantly correlated with RULA at around a 50% range (MCP 2 f-e = 53.34%, p=0.0002; MCP 2 ab-ad = 47.42%, p= .001). On the other hand, average maximum accelerations for flexion-extension and abduction-adduction at MCP2 had highly significant positive correlations at a range of around 70% (MCP 2 f-e = 69.9%, p<.0001; MCP 2 ab-ad = 70.15%, p<.0001). This extreme high correlation with accelerations of the index finger can be attributed to the fact that the rapid rise of velocities at the index finger base joint appears in the motion of the finger, and visually appeals to the observer as more strenuous.

We can surely say that the movements of the metacarpophalangeal joints of fingers were more associated with RULA than any other joint. The fact to consider here is that the MCP joint of the index finger and thumb are more responsible for determining the overall position of the fingers with respect to the hand. The change of the position of the fingers affects our perception of the posture of the hand. Therefore unlike the PIP joints in case of HAL TLV, here the factor considered is the MCP joint's movement.

In case of RULA, greater linear association was found with FDI muscle activity than with ED muscle activity; albeit the values were relatively small. The burst to average ratio at FDI muscle (r = -30.15%, p = 0.0441) significantly correlated with RULA. The negative correlation between EMG activities and RULA was baffling and counter intuitive. Again, the explanation may lie in the fact that in this study we have considered the muscular efforts related to finger motions, not the overall postural muscular effort (such as shoulder muscle EMG). Since the finger motion variables at most of the joints had an insignificant, sometimes, negative correlation with RULA, so did the corresponding muscle activity variables. In other words, having a high muscular activity at the ED muscle does not necessarily mean that the overall upper body posture is strenuous.

Out of the 48 variables tested, 14 (29.2%) were significantly correlated with RULA, and 11 (22.9%) were significantly correlated with HAL TLV. Although by pure numbers, very high correlation values appeared (around 70%) in case of RULA, it was difficult to explain and visualize the associations. Also, only the variables associated with the metacarpophalangeal joints were correlated with RULA. For HAL TLV, associations were found across almost all the joints' motions, particularly, average maximum accelerations. It was clearly explainable. Overall, we must conclude that for hand intensive operation of small devices, where repetitive motions of fingers are present, HAL TLV is a more appropriate observational tool to use. However, at this point, we cannot suggest that HAL or RULA can effectively substitute finger kinematics variables or EMG variables.

5.5 Comparison with results of existing literature

No description of finger kinematics was found in existing literature for video gaming activities. Therefore, we were not able to compare our results with similar quantitative studies. However, kinematics of the thumb and index finger joints were described for texting (Gustaffson et al., 2010), typing on keyboards (Baker et al., 2007), and on touch screen phones (Hogg, 2010).The variables measured in these studies reflect the experts' judgments of stress from these tasks. However, not all joints that we examined (MCP1, PIP1, MCP2, PIP2, DIP2) were included in the literature. Furthermore, joint velocities and accelerations were either not obtained at all, or if obtained, not in similar. In Table 5-9, we present a comparative view of the angles of relevant joints found in the above-mentioned studies and in our study. Single thumb texting was the activity mostly examined in different studies, and we found that our findings mostly corresponded with the others in terms of comparisons across joints, although the values did not exactly match.

Table 5-9 Kinematic findings from the current study and some similar studies

Study	Activity	Joint angle location	Mean value (°)
Baker et al., 2007	Typing on standard keyboard	MCP 1 f/e	1.9
		MCP 1 ab/ad	27.7
		PIP 1 f/e	18
		PIP 2 f/e	38
Gustafsson, 2010	One-thumb key press texting	MCP 1 ab/ad	15.3
		MCP 1 f/e	9.4
Hogg, 2010	Single thumb text entry on touch screen using claw grip	MCP 1 f/e	29.13
		PIP 1 f/e	41.29
Current study	Texting/browsing with thumb	MCP 1 f/e	6.8/9.66
		MCP 1 ab/ad	26.2/26.9
		PIP 1 f/e	11.6/7
		PIP 2 f/e	28.7/33.4
	Video gaming	MCP 1 f/e	10.8
		MCP 1 ab/ad	19.85
		PIP 1 f/e	16.9
		PIP 2 f/e	41.6

To get a relative idea, we have included our mean angles from natural video gaming study in table 5-9. As we can realize, the mean angle of flexion extension of the index finger PIP joint (41.6^{o}) is the maximum angle of displacement found across all the studies.

Joint velocities and accelerations were reported for keyboarding task (Baker et al., 2007) at all five finger MCP and IP joints. The tasks in current study were completely different from typing on a keyboard, but a relative idea about task strain on finger joints can be obtained by comparing current tasks with keyboarding task. Maximum mean velocity and acceleration for keyboard typing occurred at the 5th digit MCP, and the values were 48^{o}/s and 776.5^{o}/s^{2} respectively. In our thumb texting task, which we have established as the more strenuous one, mean velocities and accelerations peaked for PIP 1 flexion- extension, and the values were 43.36^{o}/s, and 511.7^{o}/s^{2}, respectively. The thumb browsing task, on the other hand, yielded very high velocities and accelerations at the MCP 1 joint for flexion extension motion. The mean velocity at this joint was 68.42^{o}/s and mean acceleration was $1086.38^{o}/s^{2}$. We certainly move our fingers much faster when we browse through contents on a touch screen than when we type on keyboards or text.

It should be noted that the strain on fingers result not only from motion or repetitiveness, but also from the applied finger force. In the current study, EMG activities of two muscles were included to indicate the strain resulting from muscular forces. The EMG average burst activities of extensor digitorum (ED) showed a wide range across these tasks, ranging from 326 mV (for thumb browsing) to 1392 mV (for natural gaming). On the other hand, the average EMG burst activities for first dorsal interosseous (FDI) muscle had a narrower range, 225 mV (for thumb browsing) to 676 mV(for natural gaming).

Muscle EMG for single thumb key press texting activity was studied in Gustaffsson et al. (2010) study; however the measures of muscular activity were different. Muscular effort was measured as “percentage of maximal voluntary muscular activity (%)”. Though we cannot directly compare the results, a comparison of muscular efforts of the two muscles can be made. For single thumb texting, Gustaffsson et al. (2010) found 4.6% MVE at FDI muscle, and 5% MVE at ED muscle. Activity of ED muscle was 108% of that of FDI muscle. In the current study, for thumb texting, average burst activity of FDI muscle was 333.1 mV, and that of ED muscle was 512.94 mV (about 153% of FDI). For thumb browsing, a similar result was found; the average burst activity of FDI muscle was 225.91 mV, and that of ED muscle was 326.37 mV (about 144% of FDI). Therefore, we would say that our results corresponded with Gustaffsson et al. (2010).

5.6 Discussions on product design interpretations and usage

It is generally suggested in standard ergonomic hand-tool design principles that the hand should maintain, as much as possible, a “neutral posture” while operating any hand tool (Sanders and McCormick, 1987). The weightless neutral body position, suggested by NASA (Tengwall et al., 1982), is considered to be the most comfortable posture for the muscles of the body because no external force acts upon the body parts. When the hand is in neutral posture (shown in Figure 5-8 Neutral posture of the hand and body), the wrist remains straight and parallel with the forearm; there is no deviation whatsoever, and the proximal interphalangeal joints are at around 150-170 degrees angle.

Figure 5-8 Neutral posture of the hand and body

While using small hand held devices, the shape and size of the devices inevitably dictate the posture of the wrist. The fingers may or may not be at a stationary posture, depending on the kind and extent of motion needed to operate the device. In the current experiment, we focused on the repetitive motion of the joint rather than the wrist position, because the wrist was stationary in our selected activities.

5.6.1 Design of video gaming controller

Joint angles, velocities and accelerations obtained from our study suggest that for any gaming task, the proximal interphalangeal (PIP2) joint of the index finger went through a very high angle of displacement (about 41 to 89 degrees) in flexion-extension. Also, particularly high angle of displacement was experienced by the metacarpophalangeal joint of the thumb (MCP1) during flexion-extension. Extremely high velocities and accelerations were achieved at PIP1, PIP2 and DIP2 joints.

The angle of the PIP2 joint flexion-extension can be attributed solely to the design of gaming consoles. As we can see in Figure 5-9, the index finger wraps around the gaming console at the PIP joint in order to be able to press the side control buttons (arrows a and b). While the PIP joint of the index finger mostly contributed to the posture and position necessary to press the buttons, DIP 2 joint was rigorously used to press the buttons.

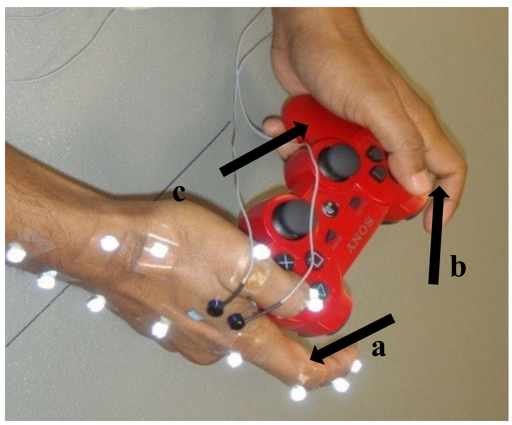


Figure 5-9 Finger position on the gaming console

Flexion extension motion of the thumb, especially at the interphalangeal (PIP1) joint, attained very high velocities and accelerations. Thumb abduction-adduction angular motion at the MCP1 joint was relatively slow, and did not attain as large displacement as other joints. This indicates that the position of the top-surface buttons and the joysticks on the gaming console are close enough for only slight abduction-adduction motion. However, the fact that there are more number of buttons to be operated by the thumb than the other fingers warrants more frequent usage of the thumb. This is what mainly contributes to the aches and pains at the thumb joints. Epidemiological evidence shows that among compulsive gamers, severe aches, pains and discomforts, including tendinitis of the hand, have occurred at the base of the thumb (Brasington, 1990; Karim, 2005).

Our biggest concern at this point with the gaming console is the contouring at the PIP joint of the index finger, and extremely high velocities and accelerations of joint motions. Therefore, we propose the following design suggestions:

i. The upper left and right corners of the gaming console should be contoured in such a way that the index finger PIP joint remains in a neutral position while holding the device.

ii. In conjunction with the above, the side buttons can be made larger so that a larger surface area of the index finger is involved in pressing it, hereby reducing the concentration of force and velocity at the DIP joint.

iii. In general, the touch-sensitivity of the buttons should be improved so that repetitive pressing can be reduced. This will reduce finger force required to activate a button, and eventually less number of presses will be warranted. This in turn may go a long way to bring repetitive joint motions to a tolerable level.

iv. Movement of the thumb, especially flexion- extension (i.e., button pressing), should be considerably reduced. We should consider distributing the keys around the console to ensure usage of other parts of the palm as well as other fingers. The thenar eminence (fleshy part of the palm below the thumb) currently supports in holding the device in hand, and touches a part of the console (Figure 5-7, arrow c). Placing some auxiliary buttons at this part may reduce the work of thumb.

v. As a general rule, video games should be designed in a way that minimizes repetitive pressing of buttons. One press of a button may be designed to perform many functions at once in the virtual arena. This way pressing many buttons at once or pressing buttons repetitively in a miniscule span of time, can be minimized. We understand that it is a part of the fun, but not at the cost of joint aches and pains.

5.6.2 Smartphone Usage

The objective of the study was to compare two techniques of single – fingered operation of smartphone. On average, joint angles, velocities, and accelerations were higher at thumb joints for thumb texting and browsing. Extremely high velocities and accelerations were experienced at the thumb joints during swiping activity. Ergonomic analysis indices indicated consistently that using single-thumb posture was more strenuous than using index-finger posture.

Our multifaceted approach unequivocally showed that thumb texting/browsing was a more strenuous task, when compared with index finger usage. Therefore, we recommend that using dominant thumb while gripping the device in the same hand should generally be avoided if possible. Using index finger of the dominant hand while holding the phone in the non-dominant hand is a better posture for single fingered operation of smartphones.

5.6.3 Risk of Cumulative Trauma Disorders

Our study did not establish the direct risks of cumulative trauma disorder (CTD)s for any of the tasks, but the information we provided can be linked to existing literature to direct us towards the possibilities of CTDs. For each of the tasks studied, we have figured out the joints of fingers where very high angular velocity and accelerations have occurred. Therefore to say the least, we know the locations where high risk of repetitive strain injury is present.

For video gaming task, Berolo et al., (2011) found that moderate pain was felt at the middle joint of the thumb by 14% of college students .The pain in that joint was also significantly associated with the time spent on gaming per day. In our study, we found that the highest average velocities and accelerations (average and max) for a natural gaming task occurred at the PIP1 joint for flexion-extension (Figure 5-2). This information corresponds with the existing data and confirms the possibility of CTD from over-use of gaming controllers at the thumb.

For texting and browsing activities using thumb, frequent inflammation has been reported at the base of the thumb (Ming et al.,2006; Gordon et al., 2008). Thumb texting generated the highest average velocities and accelerations at PIP1 joint for flexion-extension (Figure 5-4). Thumb browsing generated the highest velocities and accelerations (both average and maximum) at the MCP1 and PIP1 joints (Figure 5-6). The base of the thumb (first carpometacarpal joint and MCP1 joint) assist in the rigorous joint motion that is needed to accomplish thumb texting and browsing activities; therefore joint pains may be prevalent at those locations. Our findings are in agreement with the epidemiological information that already exists.

If we compare single-fingered texting or browsing activities using the index finger with those activities using the thumb, we can clearly see that thumb texting and browsing generated higher or comparable velocities and accelerations at almost all the joints. In literature, we find that the repetitive strain injuries related to texting have occurred at the thumb joints, especially at the base of the thumb. Therefore, we again confirm that single-fingered texting and browsing with thumb is more strenuous; and using index finger of the dominant hand to accomplish these tasks (while the device is held in the other hand) is a posture that is less likely to get CTDs.

It should be mentioned here that the repetitive strain injuries reported at different finger joints due to small hand held device use are still somewhat short-termed. What would happen to the articular cartilage of finger joints of a person who has continued to play video games for over 25 years, with or without joint damage, is yet to be discovered. The information gathered in our study can provide some insight into the matter.

Articular cartilage is a white smooth tissue covering at the end of the bones. This tissue works like bearings at the joints and makes bones easy to move over one another at the junction. But highly repetitive torsional loading can significantly damage these tissues, and once damaged, they are very difficult to repair (Buckwalter, 1998). In our study, we figured out the number of repetitive movements (strike rates) of fingers for each task. From the information gathered, we can estimate the number of repetitive movements for these tasks in a whole day. In Table 5-10, we used Berolo et al's (2011) average usage time of small devices per day to find out an estimate of the number of repetitive movement of finger joints occurring in a day for these tasks.

Table 5-10 Estimate of repetitive movements in a day

Activity	Average strike rate (strikes /min)	Usage per day (min) from Berolo et al. (2011)	Total number of repetitions in a day
Gaming	270	73.8	1195560
Texting	131.4	63	496692
Browsing	152.4	166.2	1519733

These numbers, on the average represent the daily loading on finger joints in terms of number of strikes. If we consider the amount of loading in a month or a year, an astounding number of repetitive movements will result. It is well known from theoretical stress-frequency relationship in exercise science that the higher the repetition level, the lower should be the stress experienced by any structural part of the body to avoid risk of injury (Hreljac, 2004) Combined with very high average velocity and accelerations, highly repetitive movements of fingers may ultimately result in very high joint compression forces. In the long run, damage of the articular cartilage may occur, resulting in irreversible ailments such as osteoarthritis, pain and discomfort.

Chapter 6

Conclusions

6.1 Summary of research findings

In our research objectives, we had some specific research question in mind. In this section, we attempt to answer these questions in light of our research findings.

Firstly, we wanted to know the effects of video gaming on finger (thumb and index) kinematics, muscle strain, and postural strain of the dominant hand. We used two variations of the video gaming task: one standardized gaming task, and one natural or impromptu task. We wanted to get an idea about the task strains during a standardized task and the strains in natural settings. Evidently, natural gaming task produced more strain in terms of finger movement, muscle activity, and posture. The location of the most kinematic strain was the interphalangeal joint of the thumb, and the distal interphalangeal joint of the index finger. Flexion extension of these joint was the prevalent motion in terms of joint velocity and acceleration. Electromyographic activity was higher at the extensor digitorum muscle, which assists in flexion-extension of fingers. Postural strain was significantly high for natural gaming task.

Our second concern was about the effects of using different fingers (index or thumb) for texting activities on finger kinematics, muscle strain, and postural strain of the dominant hand. Single fingered texting using thumb was found to be more strenuous in all aspects, except for muscular efforts. In this case again, interphalangeal joint of the thumb was the location where very high joint velocity and acceleration occurred.

Thirdly, we wanted to find out the effects of using different fingers (index or thumb) for browsing or swiping activities on finger kinematics, muscle strain, and postural strain of the dominant hand. In this case also, single fingered swiping with the thumb proved to be somewhat more strenuous. The metacarpophalangeal joint of the thumb went through higher joint velocities and acceleration, and flexion-extension of the thumb was the prevalent motion.

Finally, we wanted to investigate whether or not there is a significant relationship between postural strain (ergonomic variables) and kinematic variables and between postural strain and EMG variables. Two postural strain variables (HAL TLV and RULA) were correlated with the other 48 variables using Spearman correlation coefficients. Average maximum values of kinematic variables were more correlated with ergonomic postural variables than simple averages. The maximum significant correlation obtained was between RULA values and the joint accelerations at index finger MCP (for flexion-extension, r = 69%, for abduction-adduction, r = 70%). Some of the kinematic variables were found to be negatively correlated with ergonomic variables. Negative correlations were also found between RULA and EMG variables, although EMG variables were positively correlated with HAL TLV. We conclude that in these cases, the task effort of the joint represented by the intrinsic kinematic or EMG variables were not directly visible to the observers' eye; therefore low or negative correlation resulted. We also conclude that observational ratings of postural strain (ergonomic variables) did not capture the true effects of the task as measured by kinematic and EMG variables, and therefore those variables may not be appropriate substitutes for kinematic or EMG measures.

6.2 Limitations and future work

One of the limitations of our study is that the tasks were performed in a laboratory setting. We have tried to replicate the tasks as close to real life as possible, but in real life, many other postures may be adopted for these tasks. The video gaming task was performed in a sitting posture with arms and hands placed on a table. But in real living rooms, the posture may be quite different. Also, touchpads and cell phones can be used in many postures other than the ones we have explored. Future studies should include assessment of these tasks in natural settings as they occur. Also, epidemiological information can be incorporated with the current data to find out the specific reasons for musculoskeletal symptoms by looking at trends in their occurrences. Future studies should include assessment of these tasks in natural settings as they occur.

Touchscreen sizes vary a lot nowadays, and usage of other types of touchscreen devices warrants other types of hand intensive postures. Gaming consoles and video games come in numerous varieties. The intensity of the usage of fingers and wrist can be different across different gaming consoles. We limited our study to one device type (one gaming console, one video game, and one type of smartphone). Studies can be extended to include other device and game types.

Due to the intricate nature of our experimental setting, useful data was found from only a limited number of subjects. While this is fairly common in ergonomics and biomechanics studies, data from more subjects could produce more reliable results. Also, we have limited our focus on only two fingers: the thumb and the index finger. While the other fingers were not actively involved in performing the tasks in our study, postural strain may have occurred, due to prolonged constrained grasping at other finger joins as well.

Ergonomics variables used in this study were observer-dependent. Subjective opinions of the observers or raters were the basis of our ergonomic measures of task-strain. Obtaining subjective opinions from subjects regarding the difficulty or discomfort of tasks may provide useful information, which can be incorporated in future studies.

6.3 Conclusions

In this study, we have presented a motion inventory for the joints of the thumb and the index finger for three types of activities using small hand-held devices. The semi-descriptive study has provided a comparative analysis of single-fingered texting postures on touch screen smartphones. We have compiled the joint kinematics for video gaming task, which has not been done in other studies before. The information presented in this study is novel and useful. We were able to point out finger joint locations which had undergone significant strain due to repetitive motion; and this information, in turn, guided us towards specific suggestions regarding the design of gaming consoles and smartphone usage.

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Farhana Afreen Proma joined the UTA IMSE PhD program in August,2010. She has worked as a Graduate Teaching Assistant in the department from August,2010 to May,2014. She completed her B.Sc and M.Sc degrees in Industrial and Production Engineering from Bangladesh University of Engineering and Technology (BUET). She secured the first position in her B.Sc class, and was offered to join the university as a lecturer. After working as a lecturer for two years and simultaneously completing her Masters, she was promoted to Assistant Professor position. Proma has always been intrigued by the human component of an industrial environment, and wants to pursue research in human factors engineering. The lack of environment, health and safety regulations and practices in the highly labor- intensive industries of Bangladesh has been a huge concern for IE s in the country. Proma hopes to continue her research in this area to reduce these problems in her country.