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DOCTORAL DISSERTATION

Design of Multi-Position Ergonomic Computer Workstation

A thesis submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy in Mechanical and Control Engineering

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I would like to dedicate this work to my beloved father, Ayichew Workineh, who passed away when I was studying in Japan. My father made me everything who I am and I miss him so much.

In Loving Memory of

My Father

Contents

Nomenclature

θ_b	Angular parameter of backrest
θ_s	Angular parameter of seat
θ_m	Angular parameter of monitor-post
θ_f	Angular parameter of footrest
d_m	Displacement parameter of monitor-post
d_d	Displacement parameter of footrest distance
d_h	Displacement parameter of footrest height
l_b	Backrest link length
l_s	Seat link half-length
l_f	Footrest link length
s_b	Stroke of backrest actuator
s_s	Stroke of seat actuator
s_{ma}	Stroke of monitor-post angle actuator
s_{fa}	Stroke of footrest angle actuator
s_{mh}	Stroke of monitor-post height actuator
s_{fd}	Stroke of footrest distance actuator
$s_{f\mathrm{h}}$	Stroke of footrest height actuator
x_B, y_B	Position of backrest on x-y plane
x_M, y_M	Position of monitor-post on x-y plane
x_F, y_F	Position of footrest on x-y plane
θ_i^K	Minimum boundary of the ith angular parameter
θ_i	ith angular parameter

θ_i^Q	Maximum boundary of the ith angular parameter
d_i^K	Minimum boundary of the ith angular parameter
d_i	ith displacement parameter
d_i^Q	Maximum boundary of the ith displacement parameter
$S_{i,j}^H$	Stroke of the i parameter for user height H at j position
$S_{i,j}$	Stroke value of the i parameter at j position

Abbreviations

MPECW	Multi-Position Ergonomic Computer Workstation
UR	Upright Position
ZG	Zero-Gravity Position
LB	Lean-Back Position
LF	Lean-Forward Position
TP	Transitional Position
GUC	General User Comfort
RTUC	Real-Time User Comfort
OC	Overall Comfort
BPC	Body Parts Comfort

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Chapter 1

Introduction

1.1 Background

Since the first desktop personal computer was introduced to the world in 1980s, a lot of advancements have been achieved concerning new technologies to improve the computer speed, efficiency and size. We have decreased the size of the computer; designed lighter and flat monitors; developed compact laptops, and even tablets and smartphones. However, we are still bending towards our computers and working on tables and chairs, like we did many years ago when we used to work on mechanical typewriter machines. Even though studies indicated that sitting in the same position continuously decreases productivity and generally bad for workers' health in long term [1]-[7], there hasn't been a substantial development in the way we interact with computers at workplace. Nowadays, the computer is an integral part of our lives. We use computers to do almost every kind of work in companies and institutions, and even in our homes. When one talks about computer work, the computer chair and desk are the two important parts that come after the computer itself. As we have become a society that sits for a greater proportion of the day, it has made the office chair a critical component in determining our overall comfort and health. So, seats need to provide comfort, since discomfort can negatively affect overall health and productivity, especially for people who work very long hours each day [8]-[9]. For all the developments in computer design and efficiency, it is rather surprising not to see a major change in the way we interact with computers at work (Figure 1.1).

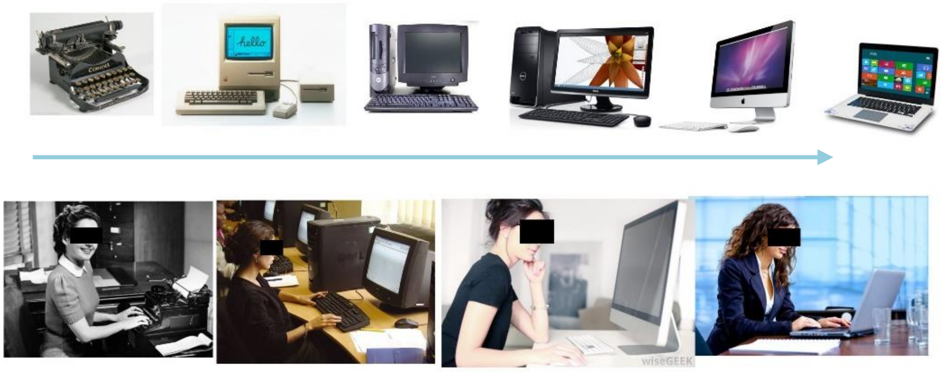


Figure 1.1 Advancement in computer design compared to the way we interact with computers

(Top: Left to right shows examples of substantial advancement in computer design and efficiency; Bottom: Left to right shows a similar way of using computers over the years)

Comfort may be defined as the absence of discomfort and vice versa [10]. Corlet et al. also defined comfort as a threshold level below which the operator would not be distracted from his/her work [11]. According to Hatch, comfort is a freedom from pain, freedom from discomfort [12]. On the contrary, discomfort is an unpleasant experience, a condition related to pain, fatigue and recognizable distress [13]. An uncomfortable computer workspace causes problems with regard to health and productivity. Discomfort and an improper sitting position for long periods leads to pain around the neck, shoulders, lower back, arms, wrists, legs and other parts of the body. Discomfort also facilitates repetitive strain injury (RSI) in the long term [14]-[17]. In 2006, nearly half a million people in the UK suffered from some form of RSI [18]. The productivity of people who work for very long periods each day will be reduced due to the uncomfortable workplace. Moreover, seat discomfort is not limited to computer work, but also distresses aircraft pilots [19], wheelchair users [20]-[21], car drivers [22] and any type of worker that spends a prolonged time in a seated position.

A lot of studies have been conducted to find optimum comfortable working position. Many kinds of designs of monitors, keyboards, desks and chairs were suggested and produced; suitable placement of monitors and keyboards were recommended; desks and chairs with adjustable heights and angular positions were proposed in order to provide better comfort during seated work and increase productivity [23]-[29]. Majority of studies has been conducted on musculoskeletal disorder focusing on lower back since the weight of upper body supported by the lower spine causes distress around lower back in the upright position. A study on the design of a backrest with different sizes of lumbar support suggested that backrest pressure decreases when appropriate size of supplementary lower back support is introduced that prevent flattening of the lumbar spine [30]. Nonetheless, most of previous studies and design improvements were based and depended on the common upright position which is the dominant (considerably 'standard') computer workstation setup. There hasn't been a major study to find a significant alternative working position for work on computers.

1.2 Literature Review

The benefits of using an adjustable chair to increase comfort and keep users in a good posture was studied [31]. Supporting workers with high performance chairs positively affected comfort and productivity. So, designing a comfortable office chair which can make posture adjustments in order to maintain comfort was recommended. To evaluate the performance of office chairs, Bush et al. measured human movement in the seated position on different chairs in terms of fit, movement and support during changes in recline and spinal curvature; the different chairs exhibited different performance [32]. From a different perspective, Robertson et al. [33] studied the effect of ergonomic training and chair intervention on musculoskeletal risk by assigning people to one of three groups: 'people with training and adjustable chair', 'people with training only' and 'other people'. The training changed the behaviour of people to help them use the office chair properly and decrease musculoskeletal risk. On the other hand, adjustable keyboard and mouse support improved the comfort level of fingers and lower back [34] while inclination of a keyboard affected the comfort of neck and head [35]. Ying Zheng and John B. Morrell [36] propose a real-time haptic feedback system that actively senses and guides a person to proper upright posture by using seven force-sensitive resistors (FSRs) for posture detection and 6 vibrotactile actuators ("tactors") for haptic feedback; However, it was limited to one position and it forced users to sit in a single sitting position (upright).

Isao Hosoe designed an ergonomic chair with a variable seat angle, positive or negative, with respect to the horizontal [37]. The design was intended to better adapt the user's height and the level of the work table in front of which the user is sitting. The designer claimed that if only the height of the seat is adjusted to work on a different height desks, a sitting person cannot assume a posture which is desirable from the viewpoint of ergonomics. However, the invention provided an ergonomic chair having adjustable seat angle and height, which was capable to overcome the drawbacks of conventional chairs. In particular it kept the centre of gravity of the person sitting along a vertical axis within the base polygon upon variation of the height and title angle. Figure 1.2 shows the invention with three types of seating positions.

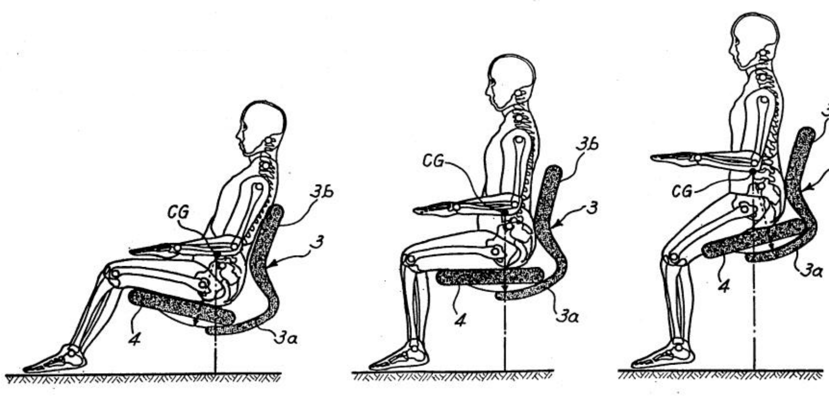


Figure 1.2 Chair design with adjustable seat angle along with height [37]

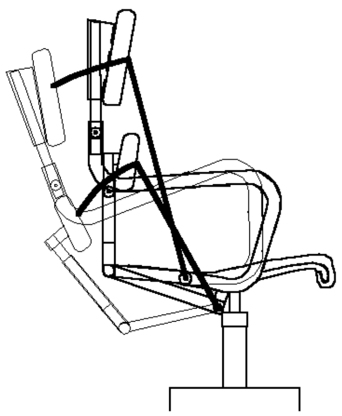


Figure 1.3 A chair design with independent upper and lower back supports (upright and alternative recline positions) [38]

A study by Faiks F. S. F. and Reinecke S. M. suggested that the backrest of a chair should follow the motion of the back while seated person changes position [38]. The backrest must, therefore, be flexible enough to provide continuous support while moving from an upright to reclined position. They developed a prototype chair consisted of two back support elements that were used to provide independent support to the lower and upper back (Figure 1.3). They investigated the magnitude of independent support to the upper and lower back. The amount of back support required at the lower region was different from the upper region. The amount of support required increased when the person reclined back. The amount of support to the upper region increased at a greater rate as a person reclines relative to the support of the lower region which gave relief to the lower region. Thus, the authors suggested that supporting natural human motion requires the proper magnitude, distribution and dynamic response of the support system; which is central to ensure that the natural motion of the spine is encouraged while being supported at all times.

A new human-machine interaction tool named Pneumatic Actuated Seating System (PASS) was developed by a team of researchers to aid in chair design [39]. The seating system was powered by thirty six designed intelligent pneumatic actuators, sixteen actuators that made up the seat and twenty actuators that made up the backrest (Figure 1.4). Three attributes were proposed for chair design: namely shape, stiffness and damping characteristics. These facilitated investigation of chair shapes from spring and damping effect of seat and backrest surface, which was formed by the contours following the user's body shape and posture. Tests were done to evaluate the prototype system and they confirmed the functionality to be used as experimental apparatus for chair design in the area of customized and specialized seating design.

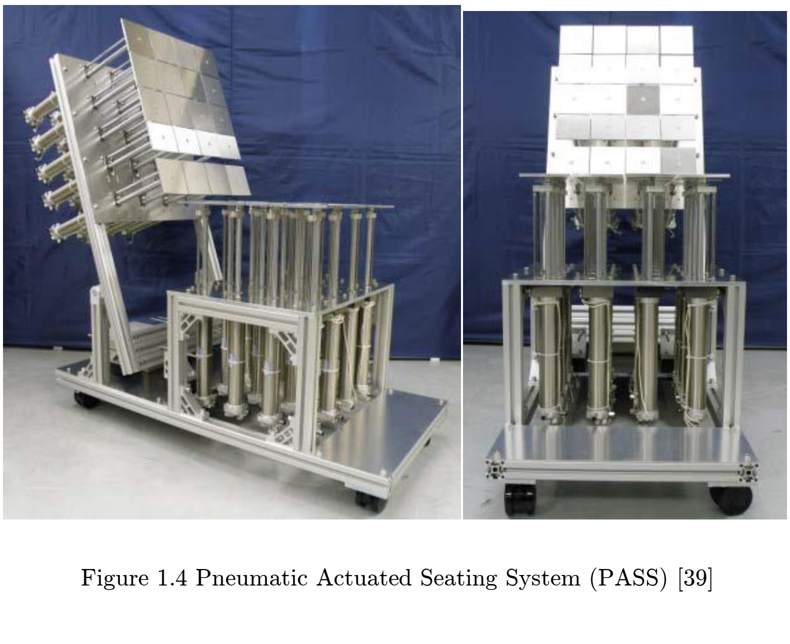


Figure 1.4 Pneumatic Actuated Seating System (PASS) [39]

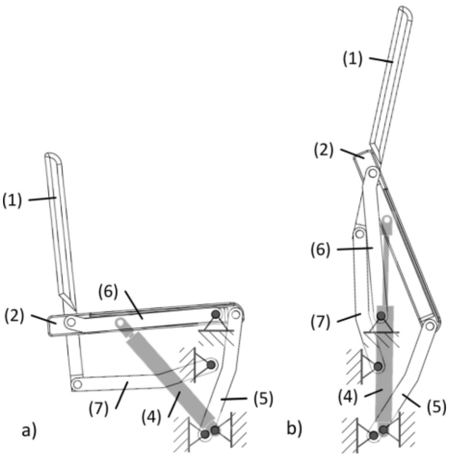


Figure 1.5 Wheelchair design with "sit to stand" mechanism [40]

(1)Backrest, (2)seat-pan, (4)gas pressure spring, (5) front bar, (6) middle bar, (7) lower bar
(a) Planar depiction of the starting configuration of the concept sit to stand. (b) Planar depiction of the ending configuration of the concept sit to stand.

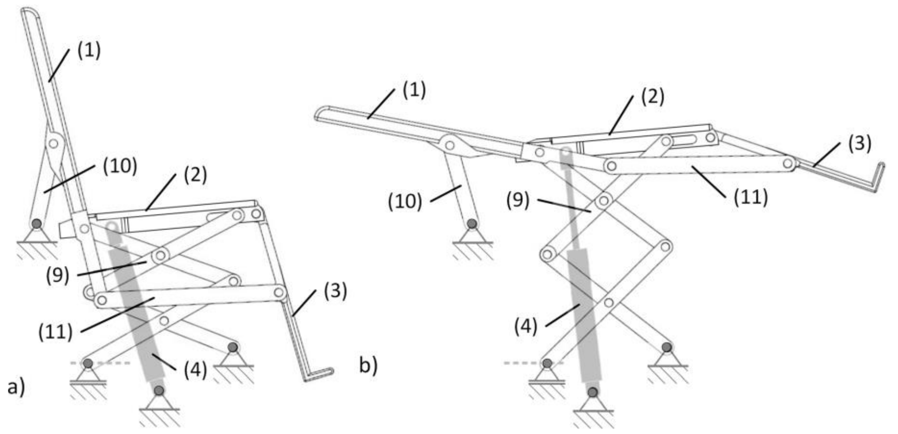


Figure 1.6 Wheelchair design with "horizontal transfer" mechanism [40]

(1)backrest, (2) seat pan, (3) legrest, (4) gas pressure spring, (9) scissors mechanism, (10) link, (11) connecting bar
(a) Planar depiction of the starting configuration of the concept horizontal transfer. (b) Planar depiction of the ending configuration of the concept horizontal transfer.

Recently, a new concept of wheelchair was introduced by Lorenzo el al. that integrated transfer support mechanism and passive actuation on wheelchairs to relieve caregivers and nurses in their daily task of lifting patients from and to the wheelchair without the need of an additional external lift device, such as commonly used lifting cranes or lifting belts [40]. They presented the design of two different mechanical linkages, where each had a single mobility actuated by a gas pressure spring. The design realized two types of transfer motions and the selection of a passive actuator for weight compensation. The first design was to support a “sit to stand” transfer which aimed assisting the manual transfer technique by reducing the force that the helper needed to apply (Figure 1.5). The second design was a “horizontal transfer” that was exclusively intended for assisting a transfer from wheelchair to bed and vise versa (Figure 1.6). The two proposed mechanisms showed that each design could realize a smooth transfer motion. Their work was similar to this research since they created a new concept where a nurse didn’t do all the work unlike the common upright wheelchair.

To assess the position of users during seated work, or the position of wheelchair users, pressure sensors were developed and actively used [41]-[42]. Hong et al. [43] developed a sensing chair using pressure sensors around the seat and the backrest of an ordinary chair to classify the type of sitting posture. Surface-mounted pressure distribution sensors were placed over the seat-pan and backrest of the chair for real time capturing of contact information between the chair and its occupant. This would make the chair aware of its occupant and the change in posture. A research conducted at University of Washington, Spinal Cord Injury System, on disable people who use wheelchairs showed that reclined postures gave a great deal of pressure relief on the buttocks and thighs (Figure 1.7) [21]. These researches also revealed that occupants change position frequently while seated, and an appropriate change in position brings comfort which indicates a need for a chair capable of changing positions following the posture of the occupant. A particular change in position could infer the emotion of the person at that moment. Due to discomfort of the seat, or other internal or external factors, a person may change positions. A study conducted in 24 sitting postures, mainly by changing the angles of trunk, neck, arms and legs, indicated that sitting postures can be associated with the emotion of the person such as sleepy, unsatisfied, irritated, tense, and etc. [44]. The same system was proposed to be used on wheelchair so that, by integrating the system with alarm system, the nurse would know when the patient attempted standing or changing to inappropriate sitting position [45]. Force sensors were also used to detect muscle activity and to measure the level of muscle fatigue in different body parts [46] which was applicable to detect distress in muscle while working on computers.

Recently, new concept designs of computer workstations are being introduced to the commercial market that intend to improve comfortability of computer work. The manufacturers claim that these dynamic workstations can increase comfort and productivity by facilitating physical activity that provide relief to a distressed body due to long time sitting. Few examples of commercially available dynamic workstation are “Treadmill Desks” (by LifeSpan, Figure 1.8(a)), “Uplift” cycling workstations (by Square Groove, Figure 1.8(b)) and “Emperor” workstation (by MWE lab, Figure 1.8(c)). Some researches that were conducted to assess these types of workstations showed that the workstations can facilitate physical activity and mainly minimize obesity, but the applicability for long time use was not significant and productivity was not significantly improved [47]-[51].

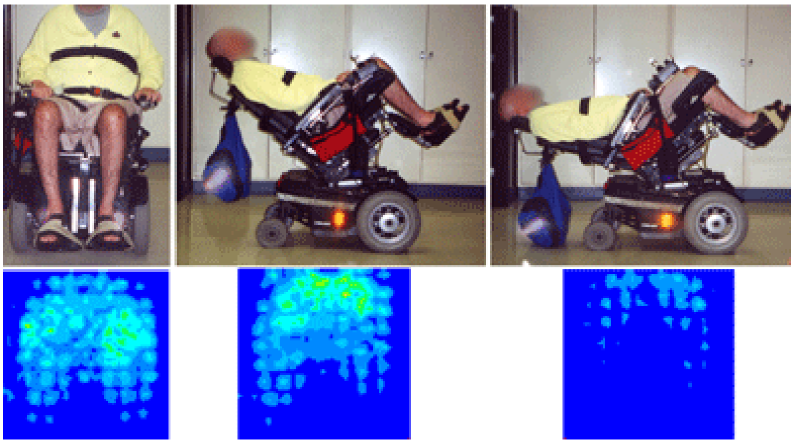


Figure 1.7 Pressure relief on seat at reclined positions [21]

Pressure maps from left to right: upright; 45 degree tilt; 45 degree tilt with recline. The tilt with recline gives the best pressure relief.

(a) (b) (c)

Figure 1.8 Commercially available workstation examples

1.3 Purpose of the Work

- **Problem statement:**

The main problems concerning uncomfortable computer workstation are related to health and productivity of workers. Discomfort at workplace for long time facilitates distress around neck, shoulders, lower back and other parts of the body. In long-term repetitive conditions, these problems may also lead to chronical disorder, especially on lower back. As a result the productivity of very long time workers will be decreased, especially for people who spend most of their work-time seated at their computer in work environments that involve heavy computer use, such as academic work, computer programing, data entry and digital media production.

Various researches that has been conducted to prevent these problems were focused more on the behaviour of workers. Most of the researchers studied about ergonomic interventions that involved training on ergonomic principles, healthy sitting behaviour and work routine while the major body part in focus was the lower back. Other researches were focused on singular issues such as improving the placements of keyboards and monitors; improving the shape of the seat and backrest; changing the cushion material; etc. Nonetheless, the majority of these studies have been conducted on the basis of the common dominant upright sitting position. Recently, a few researchers started to study on the design of workstation that allow people work in alternative working positions such as kneeling and standing.

- **Objective:**

The purpose of this research work is to improve comfortability of computer workstation by introducing a new design concept. It was anticipated that improving comfortability can reduce a distress caused by uncomfortable workstation and, as a result, a user can be healthy and productive. To achieve this objective, an ergonomic computer workstation that is capable of allowing users to sit and work in multiple alternative working positions was proposed. The new concept of computer workstation design redefined how a computer workstation was supposed to be setup.

The core idea of this new design is that working positions of users should not be restricted by the workstation setup; rather, the workstation should be able to follow the motion of users. Since sitting in one position for long time causes distress, people try to change sitting postures while working on a computer.

However, the ordinary chair-and-desk setup do not allow users to sit in different position comfortably other than upright position. Simple postural changes, like slouching forward or sideway, on a setup that was designed for upright position were indicated as improper postures that cause distress. So, we designed a Multi-Position Ergonomic Computer Workstation (MPECW) that allows users to work in various different working positions. Other specific focuses of this work are: to derive the kinematic equations of motions that govern the workstation mechanisms and to conduct a simulation of an automatic posture control system of the workstation; to analyse the effects of changing working positions on user comfort; to indicate the comfort level of different working positions; and to identify the overall improvements attained by the new design in providing a better comfort for computer users.

- **Applications:**

This research was conducted focusing on a computer workstation, and it targeted people who spend most of their work-time seated at their computers. However, the proposed theory and mechanism can be applied to similar kind of work environments that involve sitting for prolonged time. The areas of application may include, but not limited to, wheelchair designs, cockpit seat designs, cross-country truck driver seats, heavy duty machine operator seats and even car seats. The same mechanism can be used to design a comfortable wheelchair for people with disabilities that spend the major part of the day sitting on their wheelchairs.

1.4 Outline of the Thesis

The contents of this thesis are presented in six chapters.

In this first chapter, the background behind the motivation of this research and related researches conducted by different scholars are discussed to clearly define the problem and set the objectives.

In chapter two, the design of the proposed computer workstation is discussed. Ergonomic principles of computer workstation and the mechanisms of the new MPECW that enable the workstation to allow different alternative working positions are described. Four types of working positions and the development of a prototype that will be used for evaluation are also discussed.

In chapter three, the kinematics of the mechanisms of the workstation, which were developed in chapter two, is analysed to mathematically describe the setup of different working positions and the relation between actuated parts of the workstation. An automatic position control system is introduced that allow interference-free and comfortable change among the four working positions by introducing additional five transitional positions. Position control simulation results of all possible change in positions are presented.

Chapter four discusses the effects of the four types of working positions, which were defined in chapter two, on the comfort of a user. By developing a test protocol named General User Comfort and recruiting participants, tests on the prototype workstation were performed that allow participants to use the workstation in four working positions for similar task. Based on results collected from participants using questionnaire, comfort of body parts and body segments in each position is discussed. The statistical significance of comfort of each position against each other is also analysed.

Chapter five presents the results of another test protocol named Real Time User Comfort which was carried out using the same participants. This test protocol evaluates the overall comfort of the newly designed workstation as a personal computer setup including the impact on different parts of body. By collecting similar data on participants' personal workplace, comparison between the prototype and a common computer setup is also conducted to identify improvements and assess the significance difference in comfort. Findings about position control and effects due to user body size are highlighted in this chapter.

The final chapter six concludes the findings of this research work and indicates the limitation by recommending possible solutions for future improvements.

Chapter 2

Design and Ergonomics

2.1 Introduction

While sitting, people have a tendency to change positions when feel fatigue [47]; for example, extending or bending legs, extending or bending arms, leaning back or forward, etc. However, the common standard chair doesn't allow such kinds of position change due to its inflexible design. Nonetheless, users try to change positions as much as possible anyway [53]-[54]. This attempt leads to an improper sitting posture, which results in pain. Various researches that has been conducted to prevent these problems were focused more on the behaviour of workers. But, this research focuses on the design of the workstation. Thus, an ergonomic computer workstation capable of allowing users to work in multiple working positions was designed, a prototype was developed and tests were conducted. The mechanisms were designed by following ergonomic principles. In this chapter features and mechanisms of the designed workstation are presented, and selected working positions are discussed.

2.2 Conceptual Design

A workstation should be able to follow the motion of users to allow different working positions so that a change in the position of a user does not get restricted by the limitation of the setup. The common computer workstation set up limits workers to sit mainly in the upright position. Since sitting in one position for long time causes distress, people try to change sitting postures while working on a computer. However, the ordinary chair-and-desk setup do not allow users to sit in different positions comfortably other than upright position. It was indicated that slouching while sitting on an upright chair cause distress. However, it is ergonomically advised to have positional changes to relax body parts and minimize distress of long time sitting. This contradictory is due to the design limitation of the ordinary computer workstation to provide comfortable alternative positions. Thus, we wanted to create the freedom and capability of working in multiple healthy positions by designing a new workstation concept that is capable of allowing users to work in multiple alternative positions.

These alternative positions had to be comfortable and healthy postures. In addition to upright position, there are a number of postures that are seen in different environments that have shown different advantages. These positions can be adopted to be used as working postures on a computer workstation setup if the workstation is designed in order to support the body comfortably at those positions. For example, reclined position has been discussed in many researches but the reclining angle was limited since the monitor position is relatively fixed at a common workstation setup.

Basically, a computer workstation consists of chair, desk and the computer. To allow different working positions, these parts need to be flexible and interactive to each other. Keeping in mind the computer monitor could be flexible if detached from a fixed desk, we focused on the relative position of backrest, seat and footrest to create different postures during conceptual design. Additional parts like headrest, armrest and monitor-post were later introduced during mechanism design to fully support body at a given position and place the monitor appropriately. So, we chose four major postures that were significantly different to each other, and developed the conceptual, ergonomic and mechanism designs of the new workstation. Each position was defined by a main change in angular position of backrest, seat or footrest.

The new concept first had to be capable of allowing users to work at upright position. The upright position is the common sitting posture in the common ('standard') workstation setup. So it was necessary to include this posture in this concept design and use it as a reference posture. At this position, the seat was horizontal and the backrest was vertical.

A posture called Zero-Gravity position is indicated to be a balanced way of sitting in reclined position since the upper body weight and the lower body weight counterbalance at a center of gravity around the waist. This posture creates a feeling of floating as if no gravity is acting. NASA utilized this kind of sitting posture in the space program to reduce the amount of compressional forces exerted on the spine by the extreme speed at which the astronauts blast into space. This position was adopted for this workstation by mainly changing the angle of seat.

Lying down on beds is a settle posture to rest or relax the whole body parts. This position was adopted for this workstation by largely reclining the backrest. However, the backrest was not fully reclined to create a working posture rather than sleeping posture. The adapted posture is named Lean-Back position. It assumed a significantly relaxed posture, which was more like lying down on bed with a big pillow rather than a sitting posture.

Another fourth posture named Lean-Forward position was adopted from Japanese sitting style called Seiza. Seiza posture is said to be good for concentration, breathing and relief for the stomach. It also helps to stretch and keep elasticity of lower body parts. However, the original Seiza position creates extreme bent at the knees which is painful for unfamiliar and less-athletic people. So, for this workstation design, the bent angle was relaxed by tilting the seat forward and supporting knees and legs on the footrest. About 30 percent of the weight was supposed to be supported by the footrest. Children also like to lean forward when studying or writing on desk for the reason that it decreases stress in the lower back and stomach.

A computer workstation interacts with the user's body; thus, the design of this interaction determines the comfort and performance of the user. Thus the design should follow ergonomic theories and principles to create a healthy, productive and awkward-free interaction.

(a) (b) (c) (d)

Figure 2.1 Four major posture concepts of the proposed workstation design
(a) Upright, (b) Zero-Gravity, (c) Lean-Back, (d) Lean-Forward
(red annotation shows the main change in angular position of parts by taking upright as a reference)

2.3 Ergonomic Design

Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance [55]. Any kind of design for human use should pay a great attention on how the user interacts with the product. A mobile phone design, for example, should consider grip size, reachability, weight, and a lot more defining factors. A design of computer workstation should also follow ergonomic theories and principles to create a healthy and productive interaction since it interacts with the user's body; thus, determines the comfort and performance of the user.

In computer workstation ergonomics, a lot of factors and parameters should be considered to make the workstation comfortable. All body parts should feel comfortable while working on computer to avoid aches and pains that can be felt after spending long time working in front of a computer. The comfort of upper body parts, like neck, upper back, eyestrain, is mainly associated with position of backrest, monitor and headrest. The availability and/or position of armrest, the relative height of the desk, and the position of the keyboard and mouse affect the comfort of shoulder, arm, wrist and hand. The backrest design that follow the natural curve of spine and provide full support determine the comfort of lower back. Comfort of thighs depend on the seat span design and position, height of the chair along with the comfort of legs that also depend of the footrest and enough leg room. All these factors and other similar factors related to geometry and material should be taken into account for ergonomic computer workstation design.

The ergonomic design of this new workstation mainly focused on geometry and mechanisms that make the workstation flexible to enable multiple working position changes. Moreover, the shape and form of each part were also considered in the design procedure. The aesthetics and the space occupied by the whole workstation were also taken into account during the design. The workstation was designed to have simple and effective mechanisms that efficiently provide proper comfort to all body parts.

2.4 Anthropometry & Dimensioning

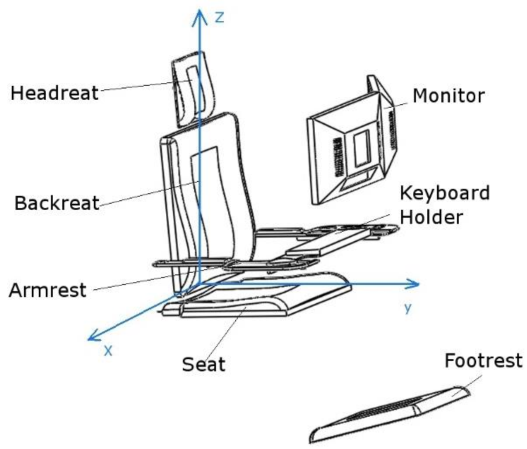
In ergonomic design anthropometry is the other main factor. The designed product should be able to accommodate a greater percentage of user population. Thus, the overall workstation and each part were designed ergonomically so that the workstation could accommodate different sizes of people. The dimensions of each part of the workstation were determined based on the minimum and maximum value of anthropometric data of 5th percentile female and 95th percentile male human size measurements [56]. The range of motion of the workstation parts, such as height adjustment of the armrest, were based on the 5th percentile female for lower limit and the 95th percentile male for upper limit.

In the same manner, anthropometric weight data was used to determine the load applied on the workstation for force and strength analysis. The workstation was designed based on the mass of the upper limit of 95th percentile male user, so that everyone below this would be included [57]. So, the workstation could safely accommodate people up to 96 kg body mass, which is of the 95 percent of the general population.

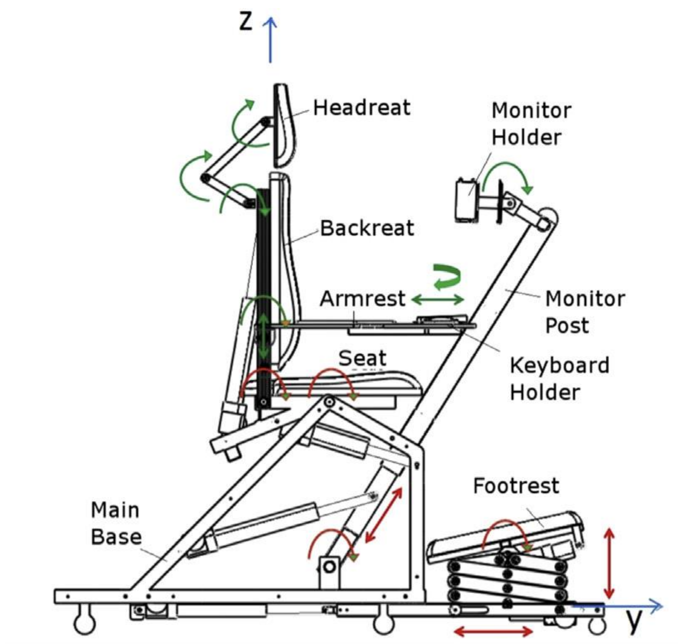
2.5 Design of Mechanisms

Design Specifications: The layout of the proposed workstation main parts is shown in Figure 2.2(a). The main parts are the headrest, backrest, armrest, seat, footrest, keyboard-holder and monitor. These parts need to be combined to one another by flexible mechanisms to attain the intended multi-position capability. The position specification of the four major positions adapted during concept design were determined based on adapted researches and ergonomic relations. The dimensions of all parts of the workstation were specified based on the lower and upper limit of the anthropometric data. The defined specifications of the four positions and anthropometric sizes were used to define and specify the minimum and maximum limits of motion moving parts. But it was also designed to accommodate many other possible positions that can be obtained within the limits of motion.

Mechanisms: All the mechanisms of the workstation were designed separately for each main part based on the specifications [58]. Figure 2.2(b) shows assembly of all the mechanisms and skeleton of the workstation with the actual dimensional proportion of all parts. Main-base, monitor-post and monitor-holder were added to complete the assembly. In total, the workstation had 19 degrees of freedom (DOF). The backrest (1DOF), seat (1DOF), footrest (3DOF) and monitor-post (2DOF) were driven by linear actuators. The headrest (3DOF), armrest (3DOF), keyboard holder (2DOF), monitor holder (1DOF) and main-base (whole body) (3DOF) were manually operated. Figure 2.3 shows the 3D model of the workstation after all parts and mechanisms were designed and modelled using SolidWorks®.



(a)



(b)

Figure 2.2 Mechanism design of the workstation

(a) Main parts of the workstation, (b) Degrees of Freedom of the mechanisms (Red: Actuated; Green: Manual)

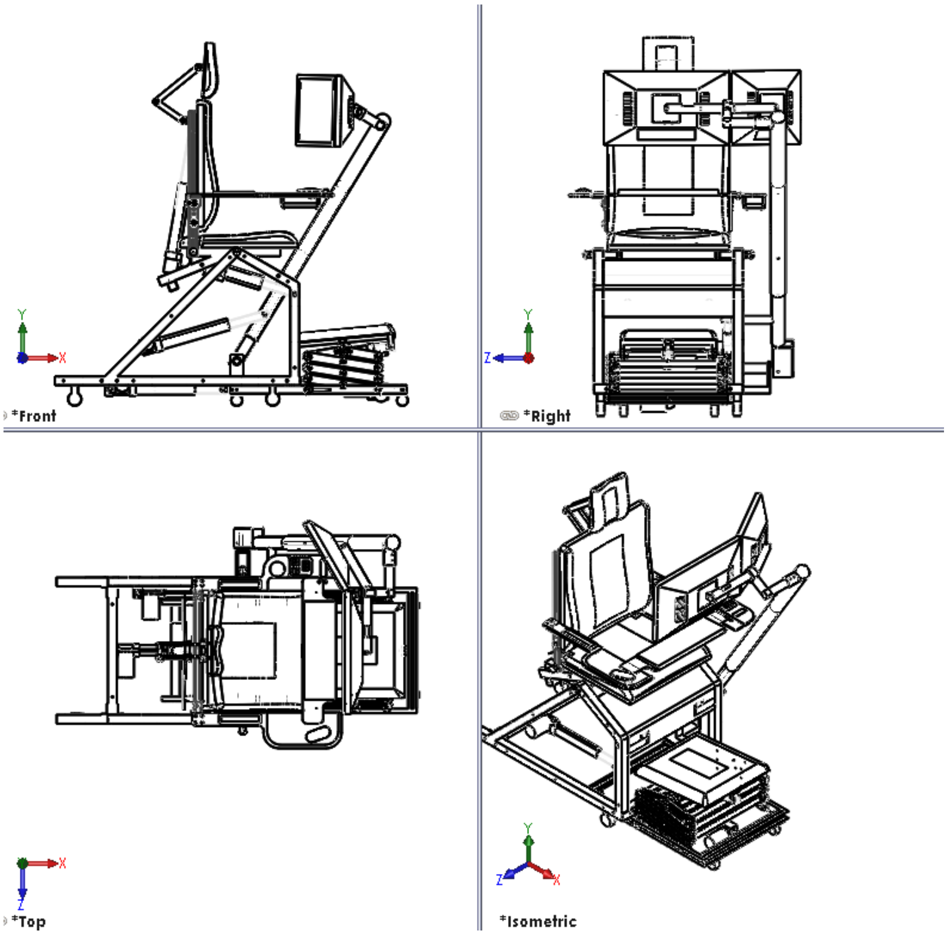


Figure 2.3 3D model of MPECW at Upright position

The mechanisms of the workstation are actuated and manually operated. Actuated mechanisms are driven by linear actuators. The position and velocity of the moving parts of the workstation directly depend on the position and velocity of the actuators, respectively. On the other hand, the positions of the manually operated mechanisms depend on the user action to move the parts between the minimum and maximum limits.

Actuated mechanisms of the workstation had 7 DOF. These were the mechanisms of the backrest, seat, monitor-post and footrest (as shown by red annotations on Figure 2.2(b)).

The mechanisms of the backrest, seat, monitor-post angle adjustment and footrest angle adjustment are of the same type of mechanisms - the inverted slider-crank mechanism. The mechanism of the footrest height adjustment is a scissors mechanism. The footrest length adjustment and the monitor post height adjustment mechanisms are simple sliding mechanisms. In Figure 2.4, the blue lines represent the actuators for inverted slider-crank mechanisms; the red line represents the actuator for scissor mechanism; and the green lines represent the simple sliding mechanisms. The yellow lines represent the driven link, which is the target moving part of the workstation, and the orange lines represent the fixed frame.

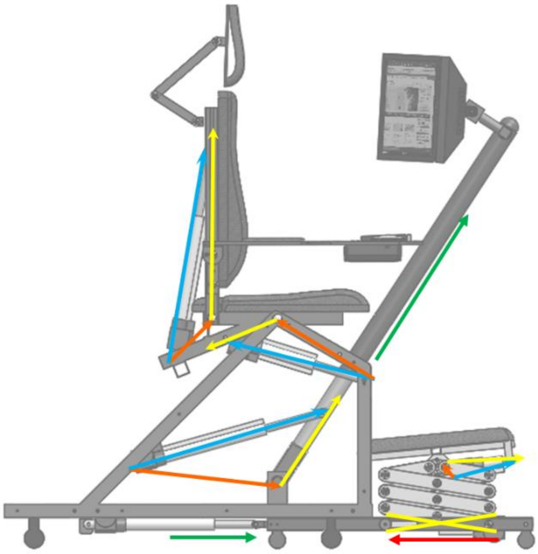


Figure 2.4 Actuated mechanisms of the workstation

2.6 Setup of Multiple Working Positions

The workstation was designed to have multiple working positions by changing the position of each moving part. It could be adjusted to any position between the upper and lower limits of each moving part. The scope of this research was not to find as many comfortable positions as possible among a lot of possible working positions; but, it was rather to assess the effect of working at alternative position on comfortability. So, four working positions that are significantly different in posture to each other were selected as described in the conceptual design (Figure 2.4).

Each working position was characterized by introducing an extreme change in position of a major workstation part. These positions were also seen in different working environments, other than computer workstation, and have shown different advantages [59]-[61]. However, the comfort of these positions was yet to be assessed in the evaluation of the workstation. Different features and speculated ergonomic advantages of these four working positions are stated below.

Upright Position (UR): This is the common sitting posture in the common ('standard') workstation setup. At this position the seat is horizontal and the backrest (also the spine) is vertical. The angles between the torso, thigh and leg are each approximately 90 degrees. This position was selected as a reference posture (Figure 2.5(a)).

Zero-Gravity Position (ZG): This is a position where the user reclines back from the seat to a certain designated angle and stretches legs above the ground to chest level. The Zero-Gravity position is shown to be a balanced way of sitting in reclined position since the upper body weight and the lower body weight counter balance at a center of gravity around the waist. In this workstation, the 35 degrees recline of the seat defined the Zero-Gravity position. The other parts followed to complement the postural balance. (Figure 2.5(b)).

Lean-Back Position (LB): This is a position where a user reclines back from the backrest and stretches legs horizontally. This position assumes a significantly relaxed posture, which is more like lying down on bed with a big pillow rather than a sitting posture. It minimizes stress on the lower back and buttocks by allowing even weight distribution. The spine will be supported following its neutral profile. The backrest is reclined 150 degrees from the horizontal. This angle creates a working posture rather than sleeping posture by optimizing the view angle to the monitor, the position of the upper body and the position of keyboard. The seat was also tilted 10 degrees back to avoid sliding to the front (Figure 2.5(c)).

Lean-Forward Position (LF): This is a position when a user tilts forward with bent legs. This position is adopted from Japanese sitting style called Seiza. However, the original Seiza position creates extreme bent at the knees which is painful for unfamiliar and less-athletic people. So, the bent angle was relaxed in this setup. The defining change in position is the 20 degrees forward tilt of the seat and the 35 degrees tilt of the footrest to support knees and legs. About 30 percent of the weight will be supported by the footrest (Figure 2.5(d)).

So, these positions were selected as a major postural changes of the new workstation to assess how changing working position improves comfortability. The positions were also successfully adopted to be used as a working postures on a computer workstation setup. The main driving elements for the change in the workstation positions were the positions of backrest, seat and/or footrest (Table 2.1). The other parts could be adjusted following the position of the main driving elements to provide the proper support and configuration. Among the four working positions, a user had options to change from current position to one of the other three positions.

(a) (b) (c) (d)

Figure 2.5 Four types of alternative working positions
(a) Upright, (b) Zero-Gravity, (c) Lean-back, (d) Lean-Forward

Table 2.1 Main angular positions settings of four working positions (deg.)

Working Positions	Backrest-Seat angle	Seat angle (measures from horizontal)	Footrest angle (measures from horizontal)
UR	90	0	5
ZG	90	35	0
LB	140	10	0
LF	110	-20	35

2.7 Development of Prototype

A prototype was developed to conduct evaluation in real time. Since the evaluation process included subjective assessment by using human subjects who used the workstation in real time, the prototype was developed in full scale. Figure 2.6 shows photographs of the developed prototype. Besides the standard joining and fitting parts and few standard configurable parts available in the market, all parts were machined, joined and developed at Tokyo Tech Mechanical machine workshop and assembled in the experiment room of Yamaura laboratory by the researcher. Parts of the workstation frames including the main base were low carbon steel material; about 60 percent of all the parts were aluminium material. The overall dimension of the workstation was 1900mm width, 1000mm depth and 1700mm height. A test of the prototype was also carried out to assess the design and mechanisms.

Figure 2.6 Prototype of the MPECW

Position of the workstation could be manipulated by controlling positions of the headrest, backrest, seat, armrest, footrest, monitor-post and keyboard-holder. All the mechanisms and control units were functional. It was observed that the user's back was properly supported following its natural spinal curve, especially on lean-back and zero-gravity positions. Arms, buttocks, thighs, legs and feet were also noticed to be properly supported in all positions. The monitor could be adjusted at ergonomically advised position for all kinds of position.

2.8 Summary

The mechanisms and parts of the new workstation concept, MPECW, were designed by following ergonomics theories and principles. The workstation was designed to accommodate a population from 5th percentile female to 95th percentile male human size. The parts of the workstation were the headrest, the backrest, the seat, the armrest, the footrest, the keyboard-holder, the monitor-post, the monitor-holder and the main-base. These parts had different mobility that complement each other and created a workstation capable of multiple positions which had 19 DOFs. The main driving parts to change positions - the backrest, the seat and the footrest - were actuated and constitute 7 DOFs including the monitor-post. The other parts were manually operated to provide a complete support for each specific position. Among multiple possible alternative positions, four working positions were selected: namely, upright, zero-gravity, lean-back and lean-forward positions. A prototype was also developed for evaluation. The overall dimension of the workstation was W1900xD1000xH1700 mm. The maximum safe load it can carry was 96 kg of user body mass.

Chapter 3

Motion Analysis and Position Control

3.1 Introduction

The workstation has 19 DOF where 7 DOF are actuated using linear actuators. Since the different working positions of the workstation are realized by the combination of the motions of these actuators, the analysis of motion and kinematic relation of mechanisms is necessary to control the position from one working position to another. In this chapter, the kinematic analysis of each actuated mechanism and the governing parameters that were used for position control are presented. The variable parameters are related to the seven actuators, and we defined 7 parameters association with the strokes of each actuator. A specific combination of the values of these parameters defines a specific position of the main parts - the backrest, seat, monitor-post and footrest - which as a result defines a specific working position. The positions of the other parts change manually to complement the positions of the main parts.

3.2 Kinematic Analysis

3.2.1 Kinematics of the Workstation Mechanisms

The main driving mechanisms for the change in position of the workstation are the mechanisms of the backrest, the seat, the monitor-post and the footrest. As mentioned before, these mechanisms are actuated by seven linear actuators and the variable parameters are associated with the stroke of each actuator.

Thus, the end positions of each actuated part (position of end effectors) can be determined from the geometric relation of the mechanisms using direct and inverse kinematics (Figure 3.1) [62]-[67]. The kinematic joints used in the mechanism are revolute (R) and Prismatic (P) joints. The geometry of the workstation mechanisms were categorized in three groups of mechanisms based on the kinematic chains (Figure 3.2(a)). The backrest and seat mechanisms together were treated as a planar Revolute-Revolute (R-R) mechanism; the monitor-post mechanism were treated as planar R-P mechanism; and the footrest mechanism were treated as planar P-P-R mechanism. The main-base was considered as the fixed part of the workstation relative to the other moving parts.

The kinematics of these mechanisms was simplified by the joint variables and the link lengths of each part as shown by the schematic in Figure 3.2 (b). The geometry of the open kinematic chain of the backrest-seat (R-R) mechanism is defined by the constant link parameters and the joint variable parameters. The constant parameters are the length of backrest, l_b, and the half-length of the seat, l_s; and the variable parameters are the joint angle of backrest, θ_b, and the joint angle of seat, θ_s. Similarly, the monitor-post (R-P) mechanism geometry is defined by the two joint variable parameters: the rotation of the monitor-post,θ_m, and the extension of the monitor-post, d_m. The footrest mechanism (R-P-P) is described by the three joint variables - θ_f, d_d and d_h, which are the angular position of the footrest, the distance and height of the footrest with respect to the main-base, respectively - and one constant parameter, l_f, half-length of the footrest.

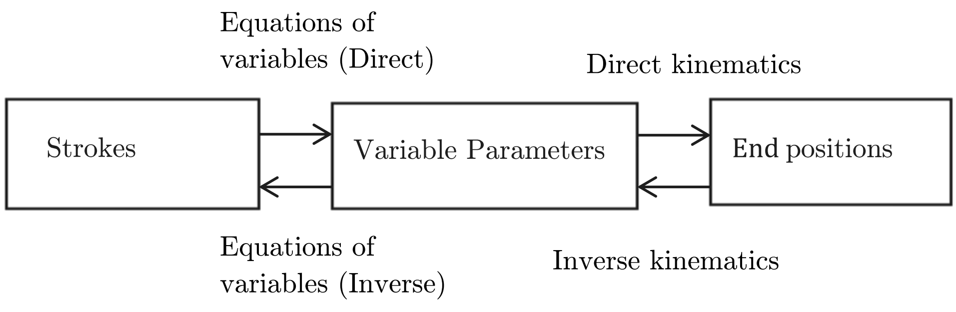
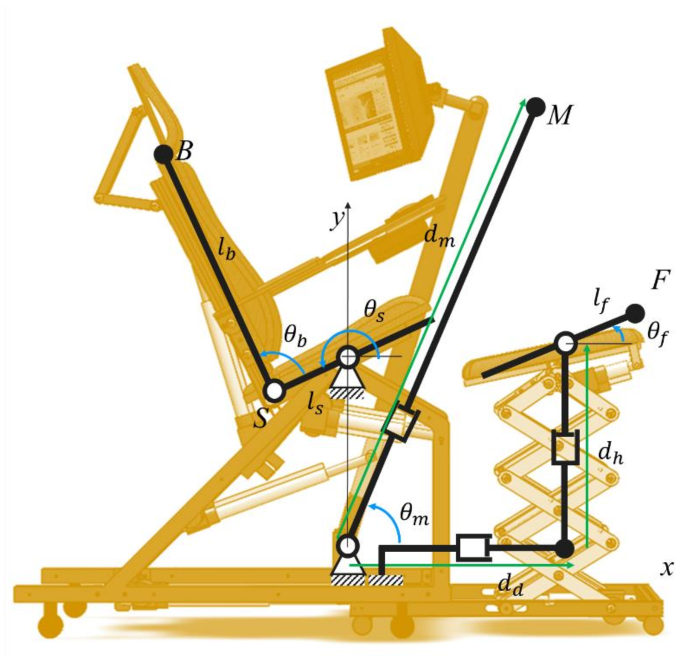


Figure 3.1 Schematics of the workstation kinematic analysis

(a)



(b)

Figure 3.2 Kinematics of the workstation mechanisms

(a) The mechanisms of the workstation grouped by three types of open kinematic chains; (b) Joint variables and link lengths of the workstation mechanism

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3.2.2 Direct Kinematic Equations

The parameters of the mechanisms are represented in Figure 3.3. The position of the backrest, *B*, the position of the seat, *S*, the position of the monitor-post, *M*, and the position of footrest, *F*, in x-y plane are expressed by using direct kinematic equations. The independent variable parameters are angular parameters of joint coordinates, θ_b, θ_s , θ_m and θ_f; and, linear parameters of displacements, d_m , d_d and d_h. The constant parameters are l_b, l_s and l_f.

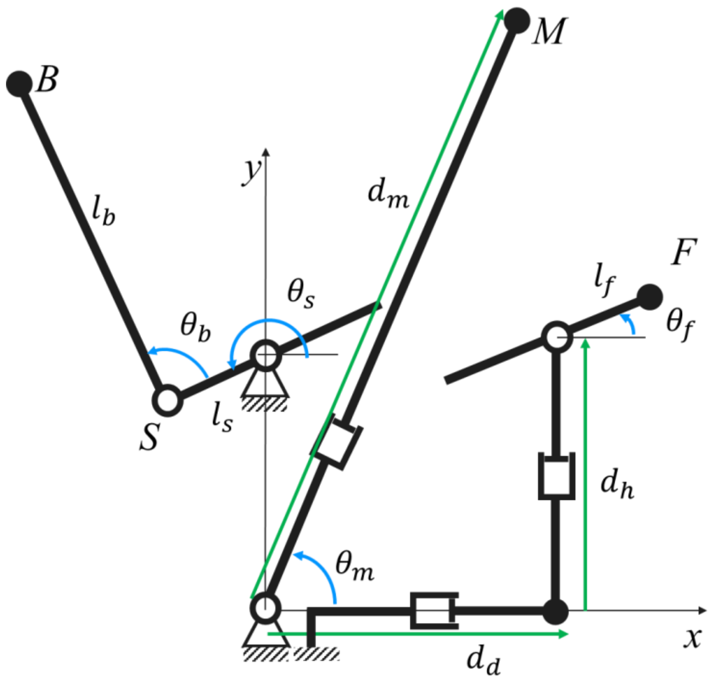


Figure 3.3 Schematic of MPECW parameters

The Backrest-Seat mechanism (R-R mechanism) is governed by the following equations:

$$x_B = l_s \cos \theta_s + l_b \cos (\theta_s + \theta_b) \tag{3.1}$$

$$y_B = l_s \sin \theta_s + l_b \sin (\theta_s + \theta_b) \tag{3.2}$$

The monitor-post mechanism (R-P) is expressed by the equation:

$$x_M = d_m \cos \theta_m \tag{3.3}$$

$$y_M = d_m \sin \theta_m \tag{3.4}$$

The footrest mechanism (R-P-P) is formulated by the equations:

$$x_F = d_d + l_f \cos \theta_f \tag{3.5}$$

$$y_F = d_h + l_f \sin \theta_f \tag{3.6}$$

The extreme positions of this workstation are lean-back and lean-forward positions. However, all variables do not exhibit extreme values during these positions. Since a specific combination of these variables creates a specific working position, the boundary limits of each variable can be determined from the maximum and minimum values that variables exhibit among the four working positions.

Assuming a variable has minimum value at a position K and a maximum value at position Q, the boundary of each parameter can be, generally, given by:

For angular parameters:

$$\theta_i^K < \theta_i < \theta_i^Q \tag{3.7}$$

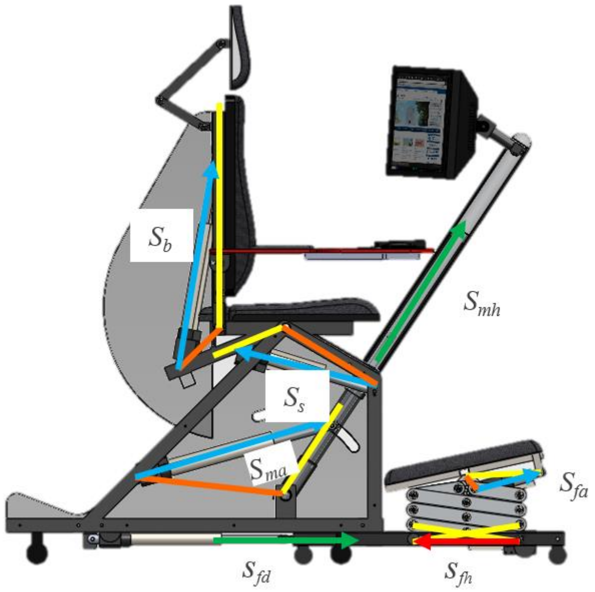
where $i = b, s, m, f$.

For linear parameters:

$$d_i^K < d_i < d_i^Q \tag{3.8}$$

where $i = m, d, h$.

However, the variable parameters are directly associated with the corresponding variable strokes of the actuator of each mechanism. The equations of variables that relate the joint parameters with the corresponding strokes were obtained from the geometry of each mechanism. Using direct kinematics, the strokes yield parameters and the parameters yield the end positions of the workstation parts; inverse kinematics was used to determine the stroke values from a given parameter (or end position) value. The geometry and joint mechanism of each workstation part was discussed in section 2.4. The variable parameters and the associated strokes of actuators are shown in Figure 3.4.



Parameter	θ_b	θ_s	θ_m	θ_f	d_m	d_d	d_h
Strokes	s_b	s_s	s_{ma}	s_{fa}	s_{mh}	s_{fd}, s_{fh}	s_{fh}

Figure 3.4 Variable parameters and the associated strokes

The backrest is joined to the seat with revolute connection. Since the backrest is actuated independently by independent backrest actuator, the seat is considered fixed relative to backrest. Thus, from the geometry in Figure 3.5, the parameter, θ_b , can be expressed by the function of the variable, s_b, as follows :

$$\theta_b = \theta_c + \cos^{-1}\left(\frac{a^2 - c^2 - r^2}{2cr}\right) \tag{3.9}$$

where $a = s_b + \text{const}$

In the equations (3.9 -3.17) where $a = s_i + \text{const}$, $i = b, s, ma, fa, mh, fd, fh$, the constant (const) value is the installation dimension of the actuator at zero stroke value. All actuators also have constant velocities (Table 3.1). The values of θ_c , c and r are also pin-to-pin constant values determined during the design.

The seat is similarly connected with the fixed base by revolute joint. Thus, from the geometry in Figure 3.6, the parameter, θ_s , can be expressed by the function of the variable, s_s, as follows :

$$\theta_s = \theta_c + \cos^{-1}\left(\frac{a^2 - c^2 - r^2}{2cr}\right) - \text{const} \tag{3.10}$$

where $a = s_s + \text{const}$

Similarly, the monitor-post is connected with the base by revolute joint (Figure 3.7(a)). The required parameter, θ_m , for the angular position of the monitor-post can be expressed by the equation:

$$\theta_m = \theta_c + \cos^{-1}\left(\frac{a^2 - c^2 - r^2}{2cr}\right) \tag{3.11}$$

where $a = \text{const} + s_{ma}$

The other parameter, d_m , of the monitor-post (Figure 3.7(b)) can be expressed in the function of the stroke of monitor-post height actuator, s_{mh}, as follows:

$$m_d = s_{mh} + \text{const} \tag{3.12}$$

The footrest mechanism has three actuators for the angular, distance and height position. Since the footrest is actuated independently by independent footrest angle actuator, the scissors mechanism can be considered fixed relative to footrest. Thus, from the geometry in Figure 3.8(a), the parameter, θ_f , can be expressed by the function of the variable, s_{fa}, as follows :

$$\theta_f = \theta_c - \cos^{-1}\left(\frac{a^2 - c^2 - r^2}{2cr}\right) \tag{3.13}$$

where, $a = s_{fa} + \text{const}$

The footrest distance mechanism is a simple sliding mechanism. However, it is also slightly affected by the height adjustment scissors mechanism (Figure 3.8(b). The parameter, d_d , can be expressed by the equation:

$$d_d = s_{fd} + \frac{S_{fh}}{2} + \text{const} \tag{3.14}$$

From the geometry of the scissors mechanism (Figure 3.8(b)), the parameter, d_h, can be determined as follows:

$$h = \sqrt{l^2 - x^2/4} \tag{3.15}$$

The scissors mechanism has $3\,^1/_2$ scissors, thus the total height, *H*, is:

$$H = 7\sqrt{l^2 - x^2/4} \tag{3.16}$$

and,

$$d_h = 7\sqrt{l^2 - x^2/4} - \text{const} \tag{3.17}$$

where, $x = s_{fh} + \text{const}$.

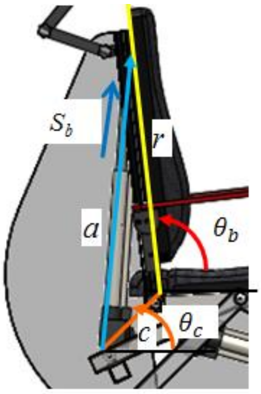


Figure 3.5 Geometry of backrest mechanism

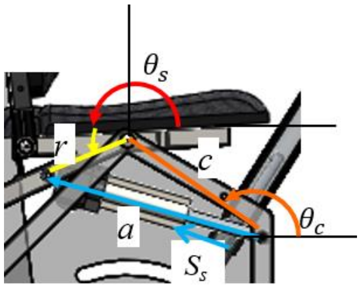
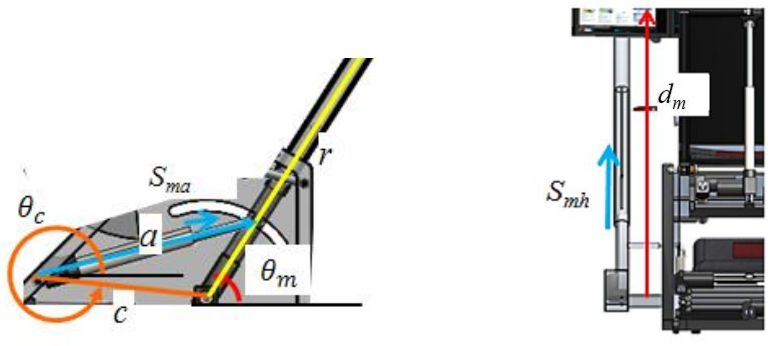
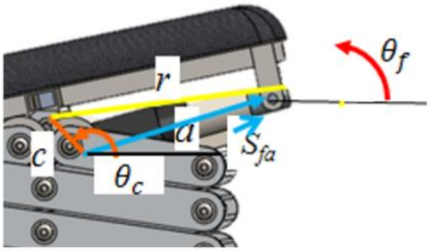


Figure 3.6 Geometry of seat mechanism

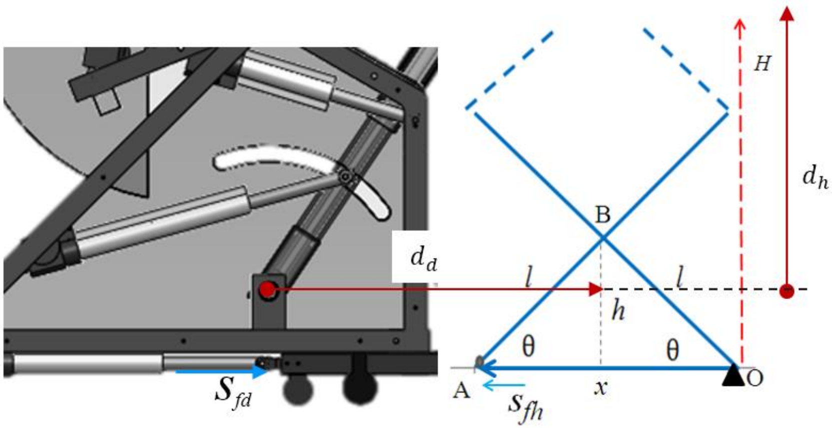


(a) (b)

Figure 3.7 Geometry of monitor-post mechanism



(a)



(b)

Figure 3.8 Geometry of footrest mechanism

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Table 3.1 Linear actuator properties

Actuator	Back -rest	Seat	Monitor -post Angle	Foot-rest Angle	Monitor -post Height	Foot-rest Distance	Foot-rest Height
Installation dimension [mm]	175	175	175	175	110	175	175
Velocity [mm/s]	4	4	4	8	20	20	8
Stroke Max. [mm]	200	150	200	40	500	250	85

.

3.3 Posture Control System

3.3.1 Working Position Change Sequence

There are four working positions: UR, ZG, LB and LF. The position control system considers what the current position is and what the target position is. A position control sequence is defined for the control system to change positions from one positon to the other in a planned and regulated manner. Considering UR position as the base position, there are six possible position change sequences, and the reverse of all, among the four positions.

Table 3.2 Possible position change sequences

	UR	ZG	LB	LF
UR	x	Forward	Forward	Forward
ZG	Reverse	x	Forward	Forward
LB	Reverse	Reverse	x	Forward
LF	Reverse	Reverse	Reverse	x

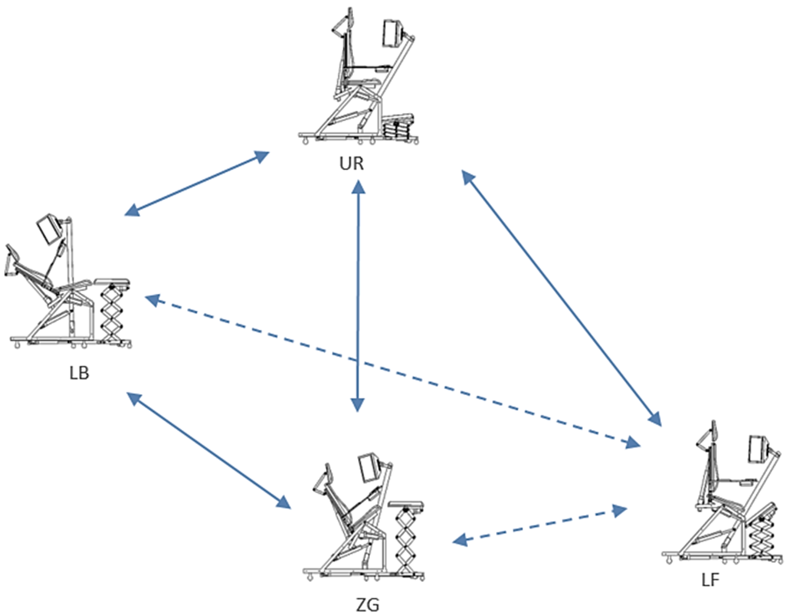


Figure 3.9 Position change sequences

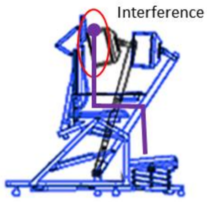
Solid lines show direct changes and dotted lines show indirect changes (Indirect pairs should follow the direct paths for smooth transition)

The possible position changes that can occur in this system are shown in Table 3.2 and, graphically, in Figure 3.9. The UR position is the reference position. The LB and ZG positions are reclined positions relative to UR; and the LF position is a forward tilted posture. So, the change from LB and ZG to LF position basically passes through UR position. The solid lines in Figure 3.9 show this direct transition and the dotted lines show the indirect changes. To avoid unnatural posture during position change, indirect pairs follow the direct paths by introducing an intermediate position that facilitate smooth position change.

3.3.2 State Diagrams

The change in position occurs when there is a change in the values of the seven defined parameters. From previous experiments that involved controlling these parameters manually and separately, a careful analysis was done to make the position change smooth, comfortable, interference-free, and faster with a minimum actuation sequence. Changing all parameters at the same time or in random order resulted unnatural/uncomfortable position and caused interference between workstation parts. Changing position of each part one-by-one also took unnecessarily longer time. So, an actuation sequences of transitional positions (TPs) were determined to avoid unnatural posture and interference while changing the position of multiple parts together to make the position transition faster. For example, during the change from UR to ZG position, if the monitor-post moved towards back before the seat reclined, the monitor would hit the face of the user since the backrest would be still vertical (Figure 3.10 (a)). To avoid this interference, the seat could be reclined first and the monitor-post could be actuated next; but, this separate action would take time. Thus, to get interference-free and faster change, the position of the seat and the monitor-post had to move simultaneously by keeping the distance between the monitor and the backrest constant, which resulted in one TP.

Based on the experimental analysis and observations, totally, five TPs were determined. The transitional positions are TP1, TP2, TP3, TP4 and TP5 (Figure 3.10(b)). These transitional positions are defined by the sequences of actuation - thus, the sequences of changing parameters - that change working position from one to another. With these transitional positions, a single position change (for example from UR to ZG) was attained by incorporating only one TP (for this example, TP1). Due to the extreme change in the footrest during LF position, the change from UR to LF required two TPs, TP4 and TP5. To allow interference-free comfortable transition when changing from ZG to LF and from LB to LF, the workstation position first had to be changed to UR position before changed to LF position. It also allowed to restrict the change in the already developed TPs. Table 3.3 shows the TPs required for each position change.



(a) Interference between monitor and backrest due to random parameter change

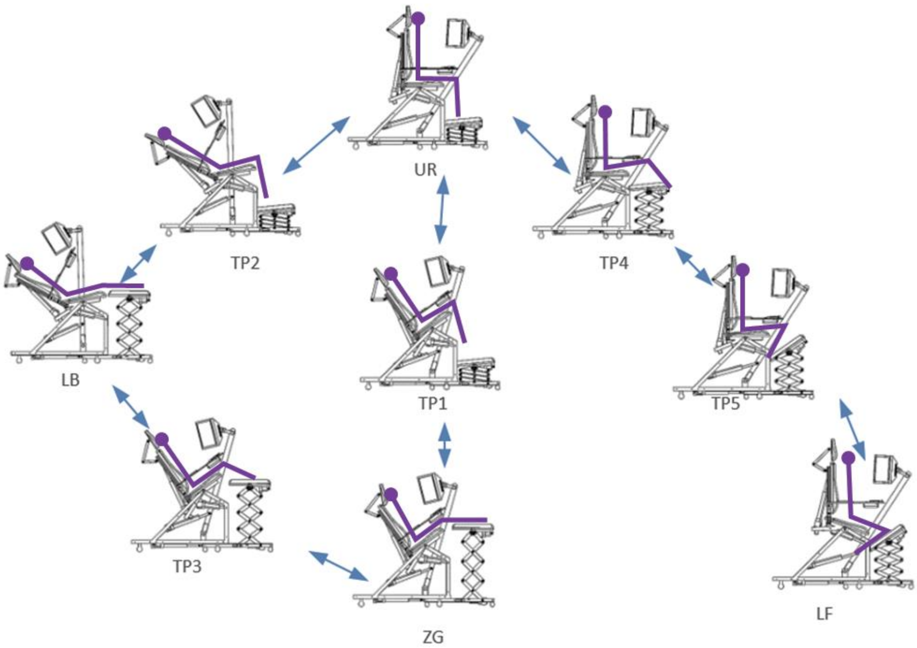


Figure 3.10 (b) State diagrams of four working positions and five transitional positions

Table 3.3 Transitional positions required for each position change

	UR	ZG	LB	LF
UR	x	TP1	TP2	TP4,TP5
ZG	Reverse	x	TP3	TP1, TP4, TP5
LB	Reverse	Reverse	x	TP2, TP4, TP5
LF	Reverse	Reverse	Reverse	x

3.3.3 Actuation Sequence and Planner

The actuation sequence defines the transitional position(s) required to change from one position to another position. The six forward, and the six reverse, positions required one or more transitional positions from the five transitional positions (Table 3.3). Overall there are 9 positions - four working positions and five transitional positions (Figure 3.10). A single actuation sequence creates a single position, so there will be 9 different actuation sequences that combine the seven parameters. All the actuation sequence steps for each parameter are shown in Figure 3.11.

The planner estimates the current position from the values of the parameters (determined by the equations of variables from the stroke values) and sets new parameters corresponding to the goal position. The corresponding stroke values are determined by the inverse equations of parameters and set as input for the actuator controller. The planner also sets the actuation sequence that govern the transition positions required to change the position from the current position to the goal position. The actuator controller for each parameter drives the actuators to the set value following the actuation sequence. These all constitutes the position control system of the workstation as shown in Figure 3.12.

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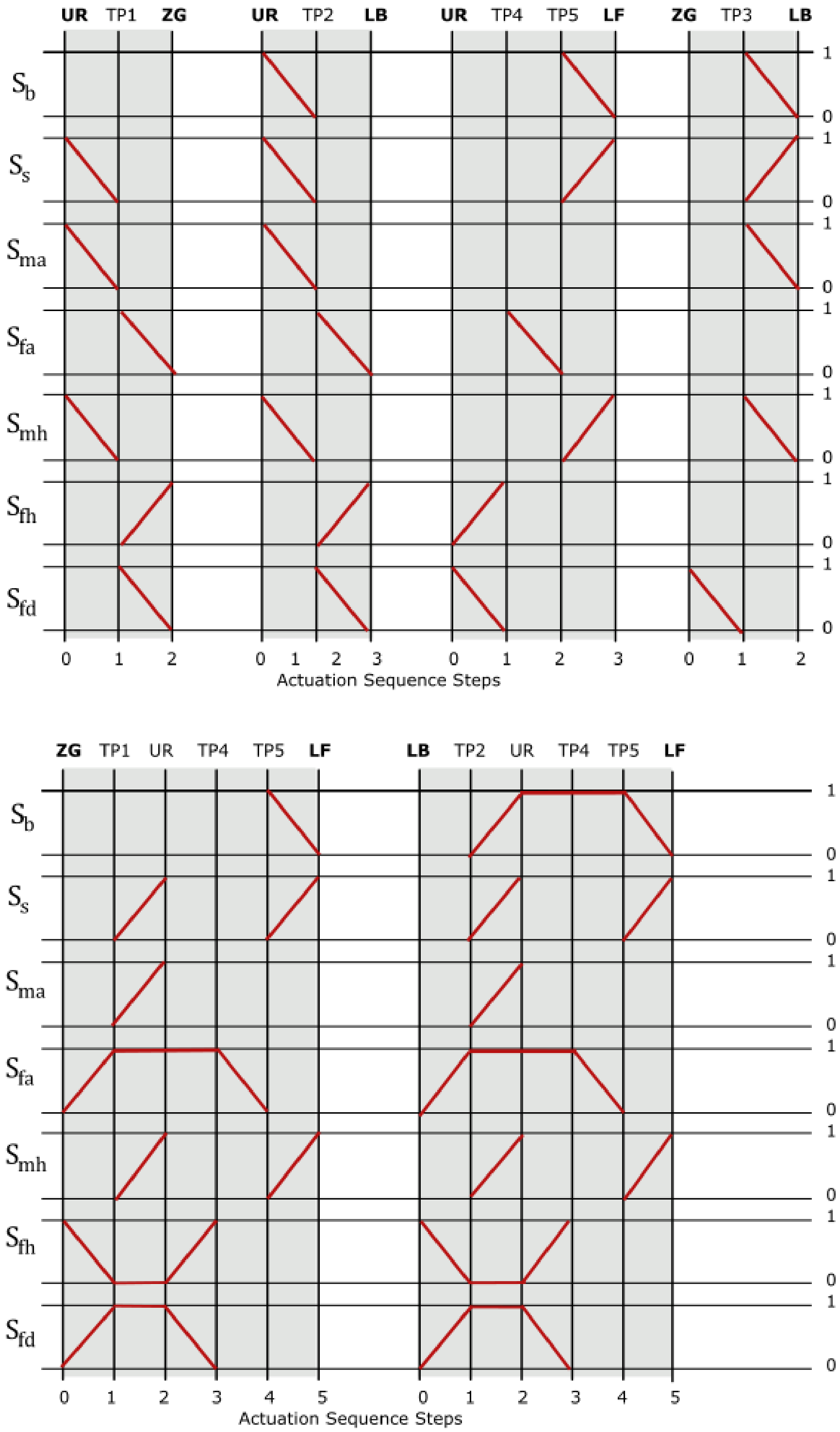

Figure 3.11 Actuation sequence of the seven actuators for all position changes

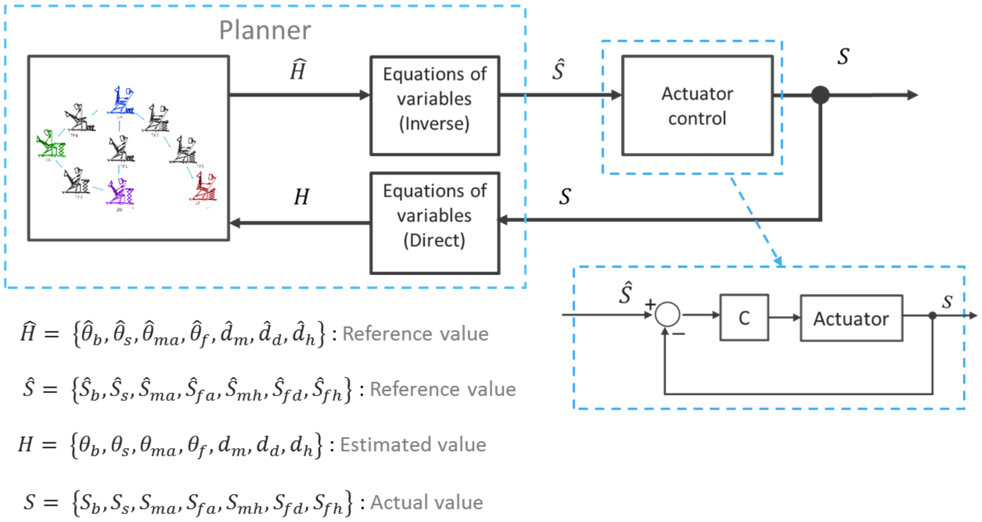

Figure 3.12 Position control system of the MPECW

3.4 Position Control Simulation Results

Position control simulation of every position change has been performed. Following the actuation sequence for each forward and reverse position change, the corresponding actuators were controlled to change the value of the parameters from the current value to the goal value. A specific combination of the values of each parameter creates a specific workstation position. The values of each parameter at the four working positions at each transitional positions are shown in Table 3.4. These values were determined for average human height of 170cm.

Table 3.4 Values of all parametric values for all positions

Position	θ_b [deg]	θ_s [deg]	θ_m [deg]	θ_f [deg]	d_m [mm]	d_d [mm]	d_h [mm]
UR	90	180	56	5	1275	488	63.5
ZG	90	215	74	0	1225	553	671
LB	140	190	88	0	1340	538	552
LF	110	160	57	35	1325	510	349
TP1	90	215	74	5	1225	488	63.5
TP2	140	190	88	5	1340	488	63.5
TP3	90	215	74	0	1225	538	552
TP4	90	180	56	5	1275	510	349
TP5	90	180	56	35	1275	510	349

3.4.1 Position control simulation from UR to ZG

The first simulation was a position control from UR position to ZG position. The initial parameters corresponding to UR position were: $\theta_b = 90\,deg$, $\theta_s = 180\,deg$, $\theta_m = 56\,deg$, $\theta_f = 5deg$, $d_m = 1275mm$, $d_d = 488mm$ and $d_h = 63.5mm$. The goal parameters corresponding to ZG were: $\theta_b = 90\,deg$, $\theta_s = 215\,deg$, $\theta_m = 74\,deg$, $\theta_f = 0\,deg$, $d_m = 1225mm$, $d_d = 553mm$ and $d_h = 671mm$. Only the backrest parameter didn't change, but all the other parameters changed. The position change required two actuation sequences: first actuation was for the seat, monitor-post angle and monitor-post height, which changed the UR position to TP1; and second actuation was for the footrest angle, height and distance, which changed TP1 to ZG position. The total time it took was 31.25 sec, which was the sum of the longest time in each actuation sequence.

Figure 3.13 shows the results of the position change from UR to ZG. In the first actuations, the values of θ_s changed from 180 to 215 deg, θ_m changed from 56 to 74 deg and d_m changed from 1275 to 1225 mm, which resulted in TP1 position. The change in θ_m was delayed by 5 sec so that it ends at the same time as θ_s, which also kept the distance between backrest and monitor constant. In the second actuation θ_f changed from 5 to 0 deg, d_d changed from 488 to 553 mm and d_h changed from 63.5 to 671 mm, which resulted the goal position of ZG position. Figure 3.19(a) shows the graphical simulation results of the position change.

3.4.2 Position control simulation from UR to LB

Figure 3.14 shows the results of the position change from UR to LB. In the first actuations, the values of the four parameters were changed: θ_b changed from 90 to 140 deg, θ_s changed from 180 to 190 deg, θ_m changed from 56 to 88 deg and d_m changed from 1275 to 1340 mm; which resulted in TP2 position. The longest time was change in θ_b. In the second actuation θ_f changed from 5 to 0 deg, d_d from 488 to 538 mm and d_h from 63.5 to 552 mm, which resulted the goal position of LB position. The total time it took was 38 sec. Figure 3.19(b) shows the graphical simulation results of the position change.

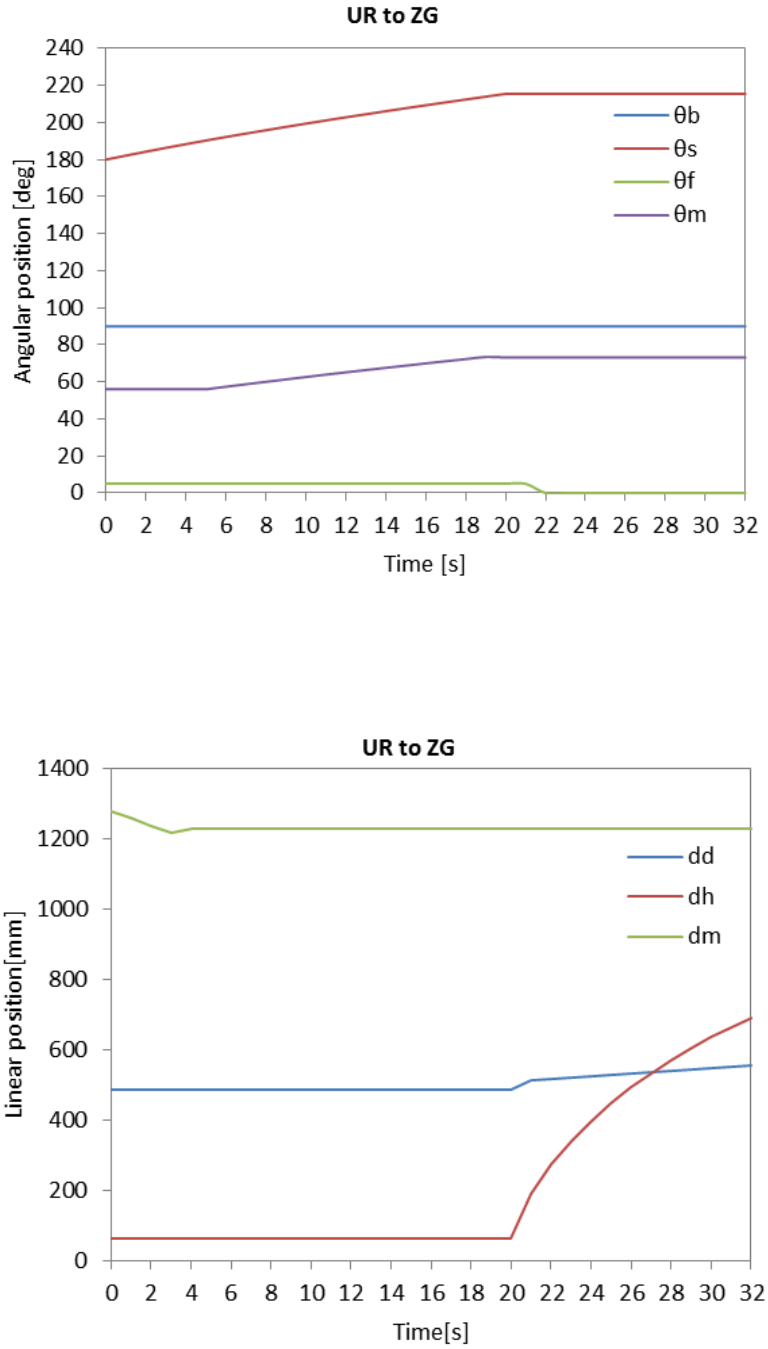

Figure 3.13 Position control results from UR to ZG position

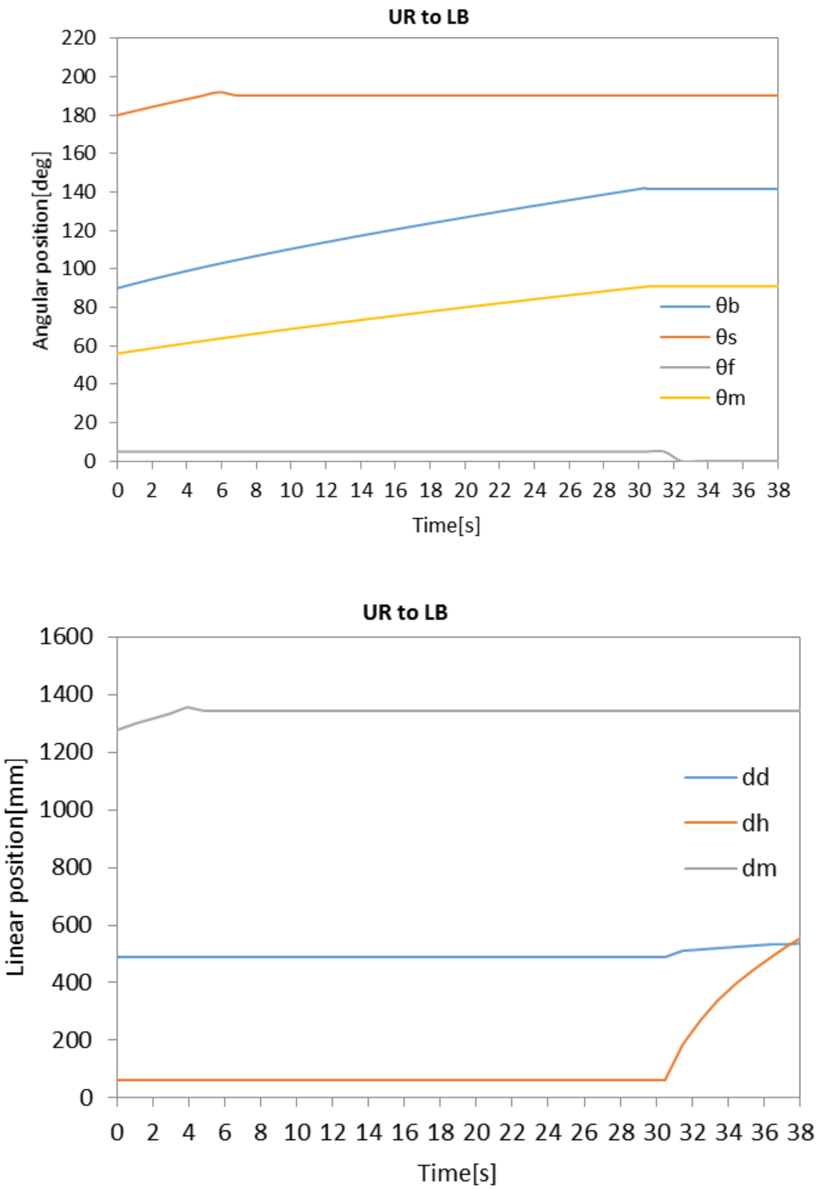

Figure 3.14 Position control results from UR to LB position

3.4.3 Position control simulation from UR to LF

The position change from UR to LF position required three actuation sequences. The first two actuations were to position the footrest at the target position comfortably without interference. Figure 3.15 shows the results of the position change from UR to LF position. In the first actuations, the values of d_d changed from 488 to 510 mm and d_h from 63.5 to 349 mm; this created TP4 position. Then, in the second actuation, only the value of θ_f changed from 5 to 35 deg, which created TP5. In the third actuation θ_b changed from 90 to 110 deg to keep the backrest virtually vertical, θ_s changed from 180 to 160 deg (20 deg of leaning forward) and d_m changed from 1275 to 1325 mm, which resulted in the goal position LF position (the change in θ_m was negligible (1 deg)). The total time it took was 15.26 sec - the shortest time of among the six position changes. Figure 3.19(c) shows the graphical simulation results of the position change.

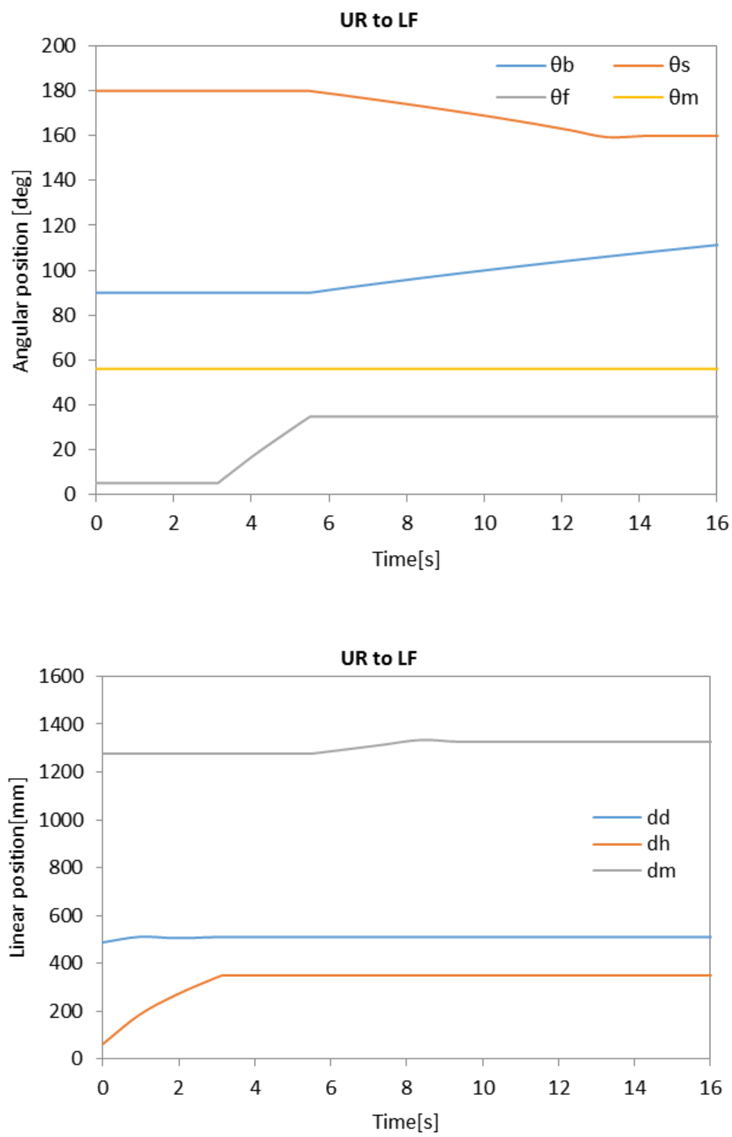

Figure 3.15 Position control results from UR to LF position

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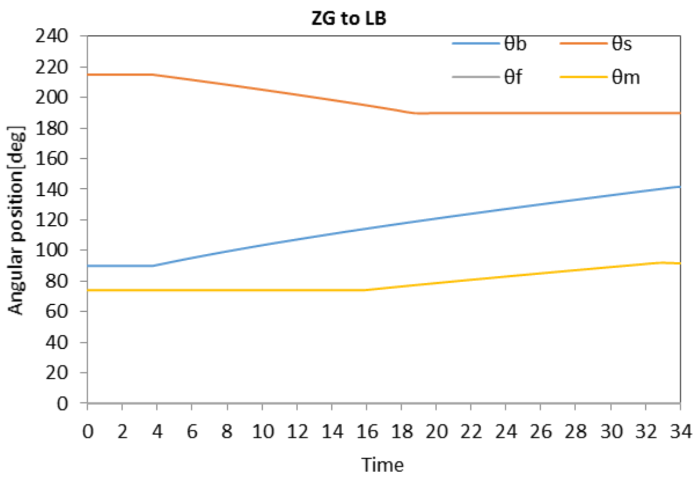
3.4.4 Position control simulation from ZG to LB

The results of the position change from ZG to LB are shown in Figure 3.16. The position change required two actuation sequences. In the first actuations, the values of the footrest parameters were changed: d_d changed from 553 to 538 mm and d_h changed from 671 to 552 mm, which created TP3. Then, θ_b changed from 90 to 140 deg, θ_s changed from 215 to 190 deg, θ_m changed from 74 to 88 deg and d_m changed from 1225 to 1340 mm; which resulted in the target position, LB position. The value of θ_f was the same for ZG and LB. The total time was 33.75 sec. Figure 3.19(d) shows the graphical simulation results of the position change.



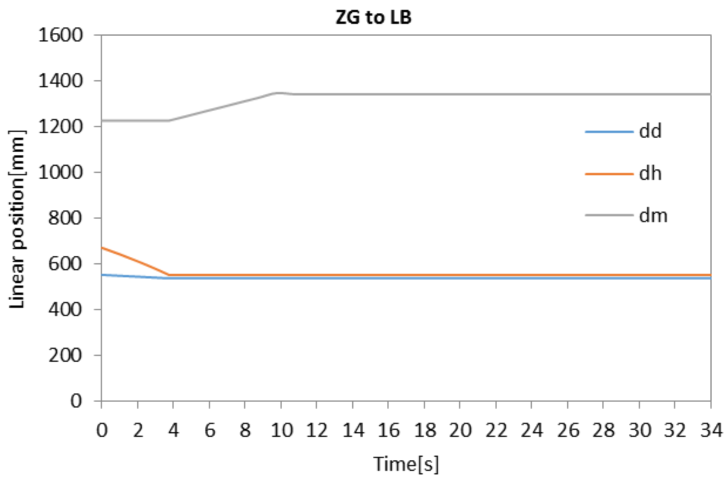


Figure 3.16 Position control results from ZG to LB position

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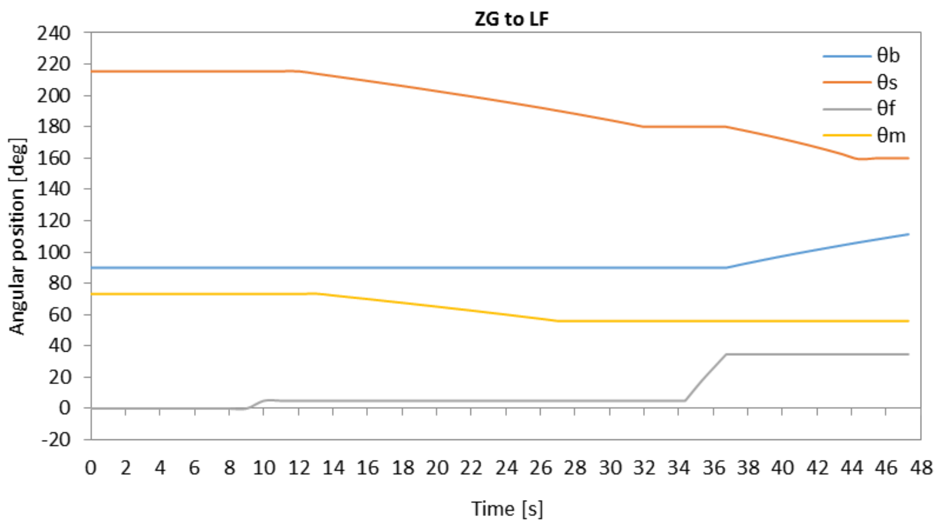
3.4.5 Position control simulation from ZG and LB to LF

The position change from ZG to LF position was the combination of the position change from ZG to UR and from UR to LF positions. The position change from ZG to UR was the reverse of UR to ZG. Thus, the whole position change had five actuation sequences: from initial position ZG to TP1, from TP1 to UR, from UR to TP4, from TP4 to TP5 and From TP5 to goal position LF. Figure 3.17 shows the results of the position change from ZG to LF. The total time was 46.51 sec. Figure 3.19(e) shows the graphical simulation results of the position change.

Similarly, the position change from LB to LF position was the combination of the position change from LB to UR and from UR to LF positions. The position change from LB to UR was the reverse of UR to LB. Thus, the whole position change had five actuation sequences: from initial position LB to TP2, from TP2 to UR, from UR to TP4, from TP4 to TP5 and From TP5 to goal position LF. Figure 3.18 shows the results of the position change from LB to LF. The total time was 53.26 sec - the longest among all position changes - which is less than a minute. Figure 3.19(f) shows the graphical simulation results of the position change.



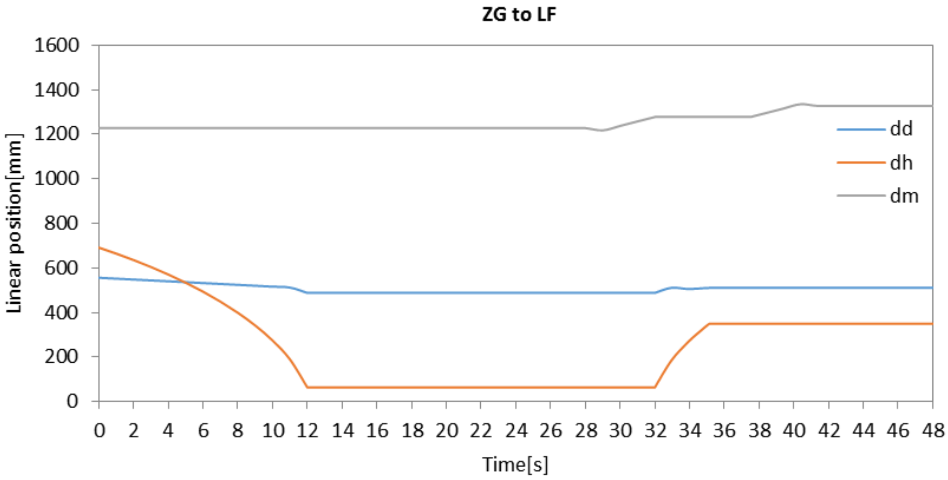


Figure 3.17 Position control results from ZG to LF position

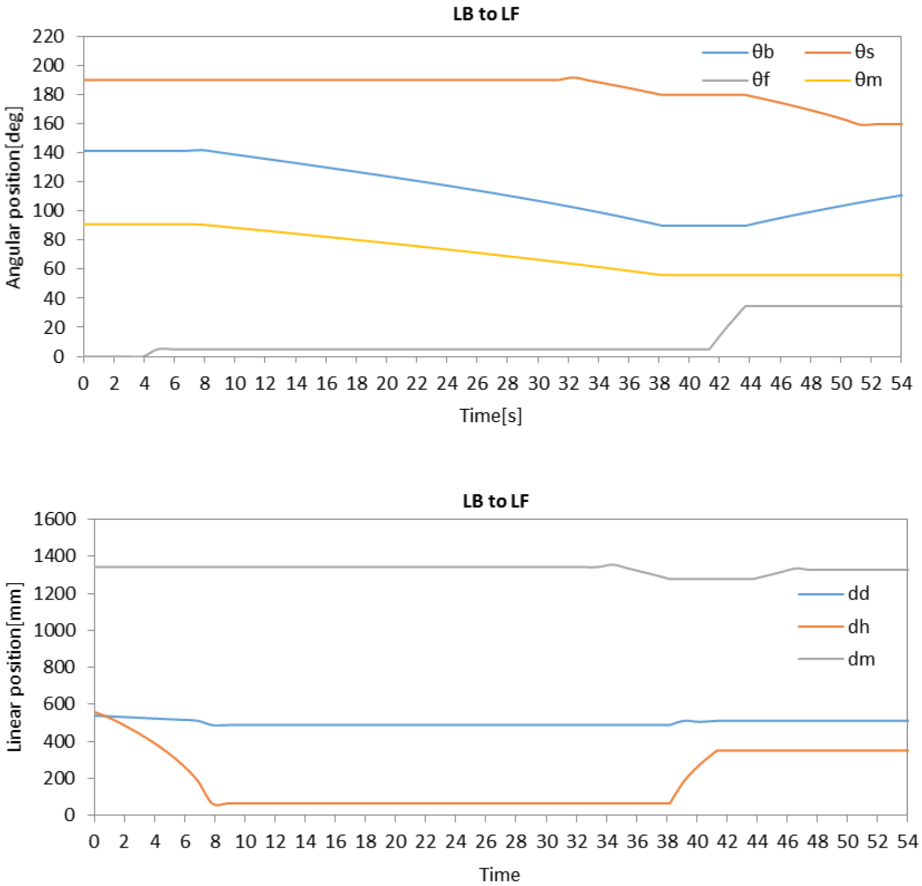


Figure 3.18 Position control results from LB to LF position

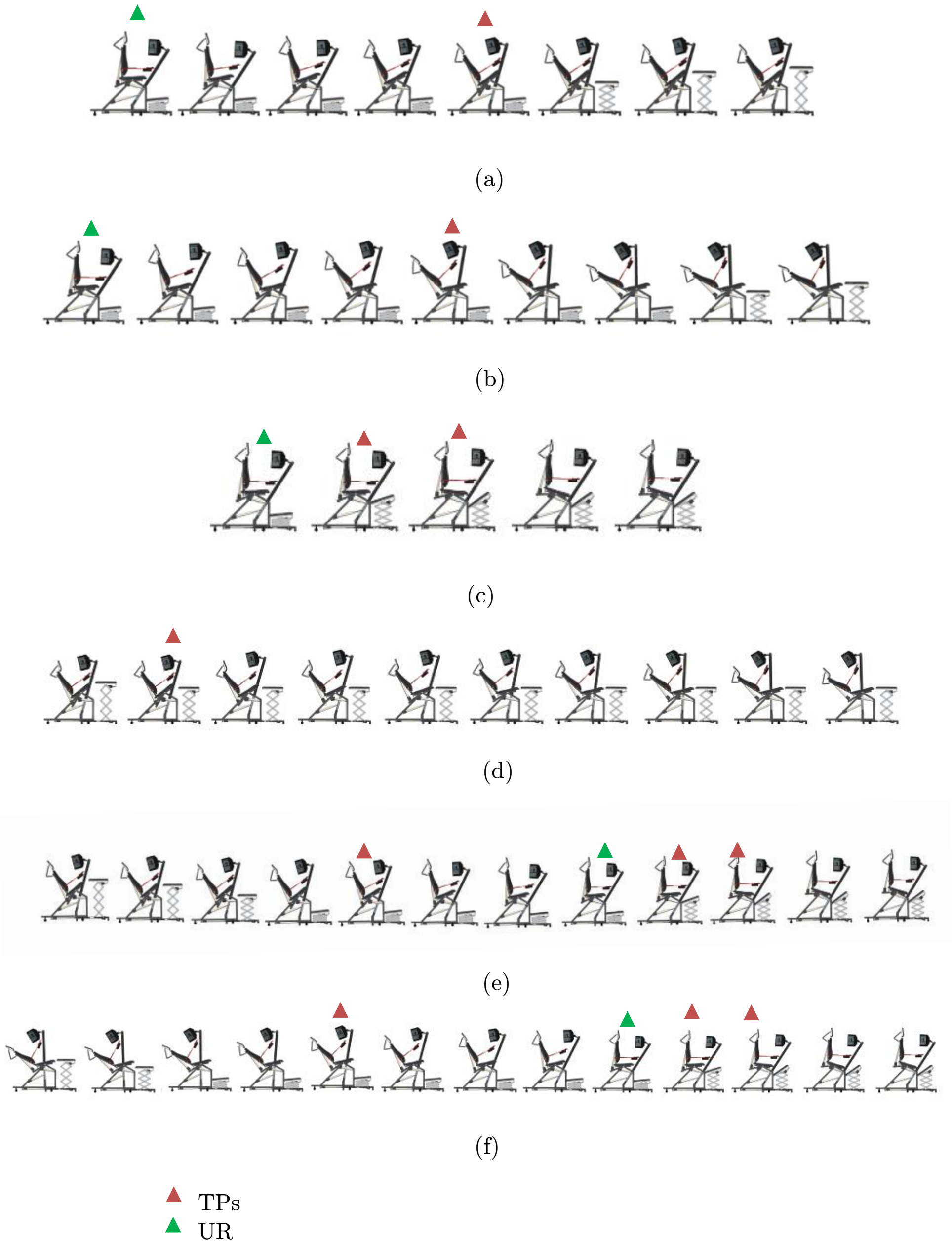


Figure 3.19 Graphical view of position control simulation
(a) UR to TP1 to ZG, (b) UR to TP2 to LB,
(c) UR to TP4 to TP5 to LF, (d) ZG to TP3 to LB,
(e) ZG to TP1 to UR to TP4 to TP5 to LF,
(f) LB to TP3 to UR to TP4 to TP5 to LF

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3.5 Summary

The workstation mechanisms were categorized in three types of mechanisms for ease of kinematic analysis and position control. The mechanisms were governed by seven parameters, four angular and three linear, which were directly associated with the corresponding strokes of each of the seven actuators. The parameters were defined in the function of the corresponding strokes using direct kinematic equations. The position change sequences between the four working positions were determined by defining transitional positions that allowed interference-free and comfortable position changes. The actuation sequence and control planner were determined for every possible position transition. These direct kinematic equation were used to determine the current position of the workstation from the strokes of actuators; and the inverse kinematic equations were used to set the stroke values of the goal position from the parameters during position control. Simulations were carried out to test the position control system. Results showed that the position control system could achieve a smooth transition from the current position to the goal position. The longest time to change from one position to another was less than a minute (53 secconds) and the shortest time was 15 seconds.

Chapter 4

Effects of Multiple Working Positions on Comfort

4.1 Introduction

The objective of this research was to design a new type of workstation that can provide a better comfort for a user by allowing the user to work in multiple working positions. To evaluate the effectiveness of the design in achieving the objective, evaluation tests were conducted by using different methods. Since the workstation allows different working positions, it was necessary to evaluate the comfort scale of each working position and find out if there was a significant difference among comfort of the positions. The overall comfort of each working position, the comfort of different body parts during each working position, and the overall comfort of the workstation in general were interesting areas in this evaluation. The effects of four selected working positions on user comfort are discussed in this chapter. The comfort of the newly designed workstation, in comparison with a standard computer setup, is discussed in the following chapter.

4.2 Methodology

One of the difficulties inherent to comfort assessment is to translate the sensation of comfort into quantifiable variables in order to measure comfort. Comfort is a state and it is a subjective feeling corresponding with positive state, relaxation, free of pain and pleasant experience which depends on the actual user in position [68]; and it includes physiological, psychological and physical satisfaction with the environment [69]. Researchers have developed different types of evaluation approaches to scale and quantify comfort. In spite of different understanding of comfort from different points of views, the methods of evaluating comfort are generally divided into subjective and objective evaluation methods [70]. The objective evaluation treats comfort objectively and tries to quantify by using ergonomic parameters. Typical variables for comfort assessment for seats and workstations are related to, but not limited to, comparing a new setup with a standardized ergonomic quantities [71], pressure distribution [72], occupant's position and geometry of posture [73]-[76]. Subjective evaluation methods are used to obtain the feelings of respondents (users) through a predesigned mechanisms like questionnaires. Many techniques for subjective evaluation have been developed and used in different researches and fields. General Comfort Rating (GCR) [77], Overall Comfort Index (OCI) [78], Body Part Discomfort Rating (BPD) [79] are few examples used to evaluate comfort subjectively.

The evaluation methods used for this test were subjective. Objective evaluations were carried out in previous work. To carry out subjective evaluation, new test protocols that suit this research approach were developed by adapting other previously developed subjective evaluation methods [80]-[81]. The test was conducted by using questionnaires to rate comfort and discomfort based on personal feelings of test subjects. Two types of subjective evaluations were carried out. A test protocol named Global User Comfort (GUC) was used to evaluate the comfort of each type of working position separately. The results of this test protocol are presented in this chapter. In addition, a test protocol named Real Time User Comfort (RTUC) was used to evaluate the overall comfort of the prototype workstation (discussed in Chapter 5).

4.2.1 Test Equipment (Prototype) Setup

A full-scale prototype of MPECW has been developed and it was used as a test equipment. Positions of the workstation could be changed by controlling the positions of actuated and non-actuated parts. These actuated parts were the backrest, the seat, the monitor-post and the footrest. The respective position of these parts determined the overall position of the workstation; and they were controlled by the control switches. A control panel of the control switches was assembled on the left hand. Non-actuated parts could be changed manually for each test subject to the respective positions. These parts were the headrest, the armrest, the keyboard and the monitors. The workstation was readily setup for the test by mounting a window desktop computer that has basic application software and internet connection. The test room environment was similar to a normal working environment.

4.2.2 Subject Recruitment

Attempts were made to include a mixture of participants of different gender, age, size and nationality. All participants were required to average 8 hr per day working on a computer. People working in heavy computer use environments, such as customer service, data entry, computer programming, media development, gaming and academic work, spend long time sitting in their workstation. Preference was given to people who spent longer periods of time working on computers. Graduate students and researchers in Engineering and technology use computer heavily and for long time. All participants were required to be ambulatory.

The evaluation was carried out by recruiting 14 subjects, nine male and five female. The average age was 28 (± 6) years, the average body mass was 62.5 (± 12.5) kg and the average height was 166 (± 16) cm. All participants were required to weigh less than or equal to 75 kg due to the load limit of the developed prototype. All participants were mentally and physically healthy, with a normal body mass index (BMI). Table 4.1 shows the breakdown of participants' age and body size.

Table 4.1 Participants' age, weight and height

	Mean (Range)
Age (yr)	28 (22 – 34)
Mass (kg)	62.5 (50 – 75)
Height (cm)	166 (150 – 182)

4.3 Test Protocol: General User Comfort (GUC)

Each participant signed a consent that contained test procedures, privacy and use of data for participating in the evaluation. Evaluation procedures used in this research were reviewed by our institute's Institutional Review Board. The participants performed the test in a scheduled manner. Each participant was instructed to sit on the workstation and perform common computer tasks. The tasks were browsing, writing, watching and reading. The tasks were grouped in to two: 'browsing & typing', which involved a lot of keyboard and mouse use, and 'watching & reading', which didn't involve keyboard and mouse as much. Users performed these tasks in each four working positions for 6-min each. The evaluator operated the controller to simulate automatic change in positions.

After the end of the test an assessment was completed by the participants. The comfort of each working position was rated by using a web-based questionnaire. In the first section of the questionnaire, a human body outline that indicated six general body parts was presented (Figure 4.1). Each body part was rated separately with a comfort scale. A participant rated his/her body part comfort for each type of working position based on the experience during the test in each working position. The six general body parts were namely: head and neck; lower back; shoulder and arm; wrist and hand; thigh and knee; and leg and foot. The rating of comfort was divided in 7 comfort scales: namely, very uncomfortable, quite uncomfortable, barely uncomfortable, normal, barely comfortable, quite comfortable and very comfortable; numerically, -3, -2, -1, 0, 1, 2 and 3, respectively. The baseline for comfort was "normal" (0) comfort scale, and was assumed as the comfort scale of a standard setup. The second section of the questionnaire were used to assess the comfort of each working position for the type of task performed.

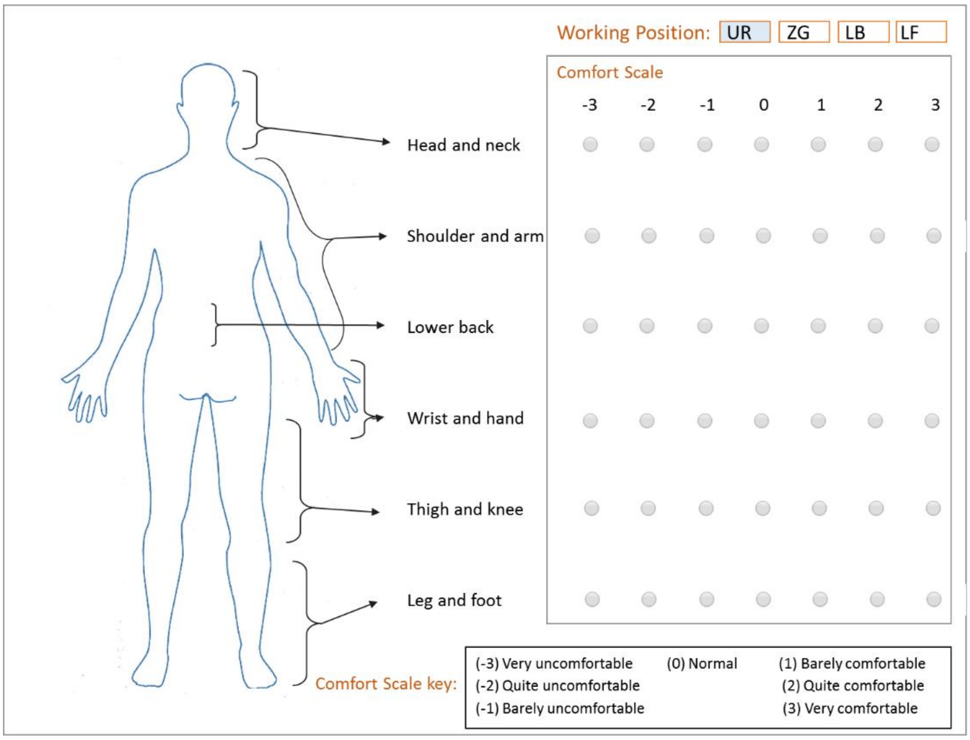

Figure 4.1 Questionnaire for GUC test protocol

(Each body part is associated with a comfort scale for the four working positions)

4.4 Data Analysis

The dependent variables recorded during testing included body parts comfort (BPC) for each of the six body parts and overall comfort (OC) of the workstation. The body parts comfort rate data was directly collected from the questionnaire. The overall comfort of each working position was calculated from body part comfort rate data.

The median of the comfort rate data for each body part was analysed for each type of working position. For further study and analysis of variance and significance, the mean values, standard deviations and standard errors were also analysed [82].

A within-subjects repeated measures analysis[1] was conducted to examine differences in means between the overall comforts of four working positions. This method was used to identify significant differences in overall comfort of subjects due to different working positions. A one-way analysis of variance (ANOVA) was performed among UR, ZG, LB and LF positions. The single factor of the analysis was 'the type of position' and it had four levels (UR, ZG, LB and LF). If a significant difference was found among the four positions, a post-hoc t-test[2] was performed to determine which positions were significantly different from the others. Bonferroni correction[3] method was used to correct the significance p-value during t-test. Then, a pair-wise comparison[4] was run to indicate which position had the greatest impact on overall comfort.

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[1] Within-subjects factors involve comparisons of the same subjects under different conditions; it tests difference by comparing the scores of a subject in one condition to the scores of the same subject in other conditions.

[2] A post hoc t-test can be used to determine the significant differences between two groups.

[3] The Bonferroni correction is an adjustment made to P-values when several dependent or independent statistical tests are being performed simultaneously on a single data set. To perform a Bonferroni correction, divide the critical P-value by the number of comparisons being made.

[4] Pairwise comparison is a process of comparing entities in pairs to judge which of each entity is preferred, or has a greater amount of some quantitative property, or whether or not the two entities are identical.

4.5 Results and Discussion

4.5.1 Body Parts Comfort by Position

The comfort rate of each body part in each type of working position was analysed and the median value was preferred to show the results since it is a more rounded number and there were no significant differences between the mean and median values. Results are presented for each working position separately in the following sub-sections. The results are discussed based on the analysis of collected data, video/picture taken and observation during evaluation process.

4.5.1.1 Upright Position

In this position users didn't feel discomfort in all body parts (comfort scale > 0) (Figure 4.2). The higher comfort scale in shoulder and arm (comfort scale = 2.5) shows that the armrest and keyboard were at a proper position. Again, the comfort of wrist and hand indicates keyboard and mouse were at a comfortable position.

Even though there was no discomfort in all body parts, the comfort of head, neck, leg and foot were lower. At upright position users did not usually use the headrest. Also, at upright position with proper seat height, the footrest was not necessary; the ground can be used as footrest. The result indicated that the headrest and footrest of the prototype did not create much difference in comfort at upright position. By also changing the angular position of seat and backrest, a better configuration may be found.

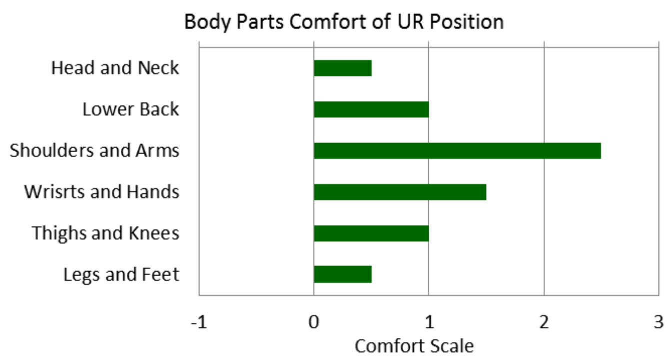

Figure 4.2 Body Part Comfort results of UR position

4.5.1.2 Zero-Gravity Position

Most of body parts felt quite comfortable (comfort scale = 2) at zero-gravity position. The headrest played important role in supporting head and neck at zero-gravity position to provide better comfort (comfort scale = 2). This position also was quite comfortable (comfort scale = 2) for lower back area. The thigh, knee, leg and foot comfort was also very good (comfort scale = 2). The footrest at a height of chest during this reclined posture supported the stretched legs evenly and avoided discomfort. The weight of the user was supported not only by the seat but also by the backrest and footrest. This avoided hot spots (high stress areas) in the body which provided relief to lower back. The monitor was also adjusted to a comfortable position to work at this position (Figure 4.3).

Since, the armrest was slant which created unsupported weight component of arm and hand, the comfort of shoulder, arm, wrist and hand was lower than the other body parts (Figure 4.4).

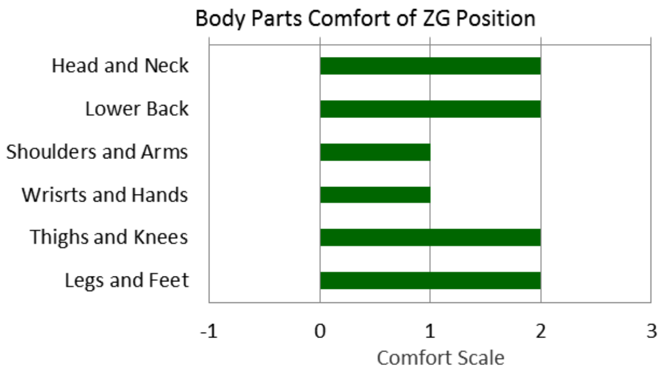

Figure 4.3 Body part comfort results of ZG position

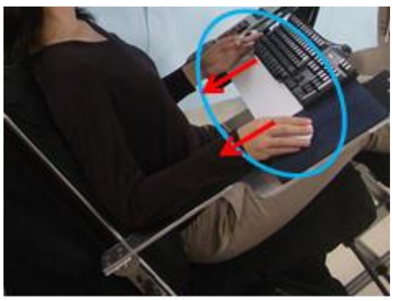

Figure 4.4 Position of hand at ZG position

Red arrows show the direction of unsupported weight component

4.5.1.3 Lean-Back Position

The results showed that most of the body parts felt more than quite comfortable at lean back position (Figure 4.5). Alike ZG position, the headrest played important role in supporting head and neck at lean back position to provide better comfort (comfort scale = 2.5). This position made users feel quite comfortable (comfort scale = 2.5) around lower back area, which was the most sensitive area to feel pain during computer work. The thigh, knee, leg and foot comfort was also very good. The footrest at equal height with the seat at lean-back position supported the stretched legs evenly and avoided discomfort. Unlike upright position, the weight of the user was supported not only by the seat but also by the backrest and footrest. This avoided hot spots (high stress areas) in the body which provided relief to lower back. The monitor was also adjusted to a comfortable position to work at this position.

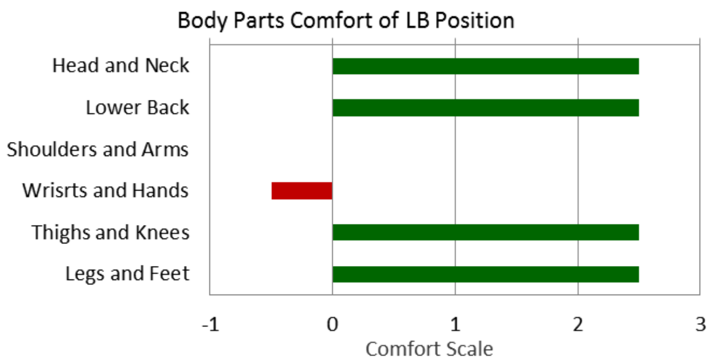

Figure 4.5Body part Comfort results of LB position

Figure 4.6 Position of hand at LB position

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However, at lean back position wrist and hand felt discomfort. When the backrest reclined back, the armrest along with keyboard and mouse also reclined back, greater than the inclination during ZG position. The angle of armrest from the horizontal became around 60 degrees. That means, total weight of the arm and hand was not supported by the armrest which caused the arm to slide back on the armrest. Even though there was a support at the elbow, the reaction produced in the shoulder joints to resist sliding caused discomfort in the shoulders and arms. The position of arms and hands during using keyboard and mouse at lean back position are shown in Figure 4.6. The hands and arms tended to slide in the direction shown. This problem can be solved by adopting new input methods like trackball, gesture, touchpad, etc.; and by improving the design of armrest and elbow support. By also changing the angular position of seat and backrest, a better configuration may be found.

4.5.1.4 Lean-Forward Position

The results of lean forward position are shown in Figure 4.7 below. At this position, there was no discomfort in body parts. The comfort scale of wrists and hands at lean forward position were similar to comfort scale at upright position since the position of the armrest was the same for both positions. The monitor was comfortable in the same way as in other positions. The lower back, head & neck comfort results were normal.

The legs, feet, thighs and knees were expected to feel more comfortable than the results. This position was essentially suggested to stretch the muscles of legs and thighs by bending legs and supporting at knees. This position would give relief to stomach and lower back by giving room to relax and by supporting 30% of weight on footrest. However, these effects could be seen more significantly after a user felt discomfort around legs due to sitting long time at other positions. The time during evaluation was not long enough to see the advantages of this posture, but personal tests and other evaluation results showed that it was more comfortable than these results.

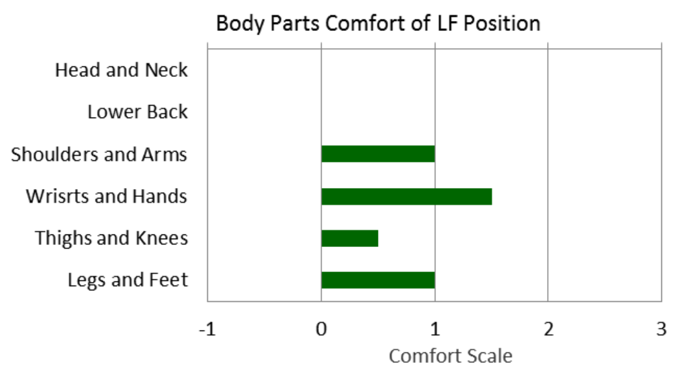


Figure 4.7 Body part comfort results of LF position

4.5.2 Comfort of Body Segment by Position

The effects of each working position on the comfort of body parts were different as discussed in the previous section. To see if the comfort was localized in certain body segments, the body parts were grouped into three body segments: upper extremity, trunk and lower extremity. Table 4.2 shows how the body parts were grouped in three main body segments. This analysis also helped to identify how the change in working position affected the comfort of body segments and which working position was better for different body segments. Figure 4.8 shows the comfort of body segments in relation to each working position.

The results revealed that the comfort of middle and lower extremity increased when the working position was reclined back; however, the upper extremity comfort was noticed decreasing. This means that the middle and lower extremity become more balanced and fully supported by the workstation when reclining. The weight of the user got distributed along the contact surface of the body with the workstation. The lowest comfort scale of all body segments (thus all body parts) was registered during working in lean-forward position. Improving the support mechanisms of upper extremity and using custom-made keyboard and mouse would noticeably improve the comfort of these body parts during working in reclined positions.

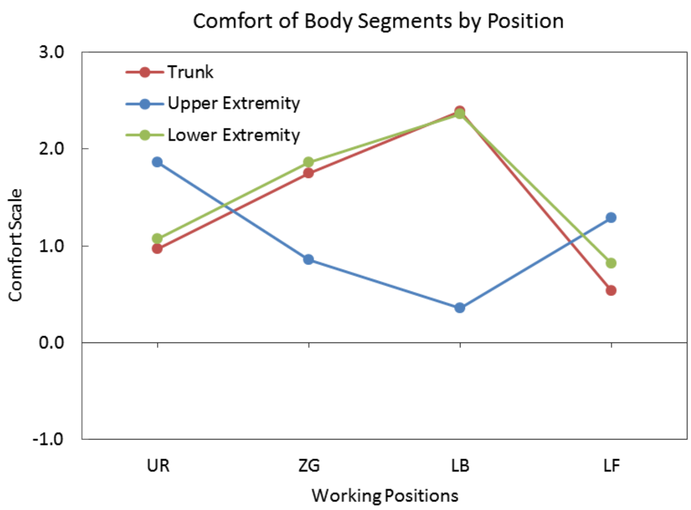


Figure 4.8 Comfort of body segments relative to working positions

Table 4.2 Body parts grouped in body segments

Upper Extremity	Trunk	Lower Extremity
Shoulders	Head	Thighs
Arms	Neck	Knees
Wrists	Lower back	Legs
Hands		Feet

4.5.3 Overall Comfort by Position

The results showed that the overall comfort of users was improved by 43.3%, 49%, 56.6% and 29.3% on average during UR, ZG, LB and LF positions, respectively. To determine if there was a significance difference between the overall comforts of working positions, the overall comfort of each working position was statistically analysed. A test of within-subjects analysis revealed that there was a significant impact on overall comfort based on working positions, $F(3,52) = 3.299$, $p < 0.05$. Figure 4.9 shows the mean overall comfort of each working position with error bars indicating plus and minus one standard error.

A post-hoc t-test was performed to determine which working positions were significantly different from the others. The significance p-value was corrected using Bonferroni correction method. The results showed that lean-forward position comfort was significantly lower than lean-back position, $t(26) = 3.256$, $p < 0.05$. However, there was no significant difference between the other pairs of working positions: between UR and ZG, $t(26) = -0.657$, $p > 0.05$; between UR and LB, $t(26) = -1.377$, $p > 0.05$; between UR and LF, $t(26) = -1.406$, $p > 0.05$; between ZG and LB, $t(26) = -0.874$, $p > 0.05$; and between ZG and LF, $t(26) = 2.452$, $p > 0.05$.

A pairwise comparison between the working positions revealed that the comfort of lean-forward position was rated significantly lower. The differences in mean comfort values between the four working positions are listed in Table 4.3.

Table 4.3 Pairwise comparison of comfort of overall comfort

Working Position(mean)	ZG (1.488)	LB (1.702)	LF (0.881)
UR (1.298)	-0.190	-0.405	0.417
ZG (1.488)		-0.214	0.607
LB (1.702)			0.821*

*$p < 0.05$
the different in mean comfort of body parts based on prototype setup, (row) - (column)

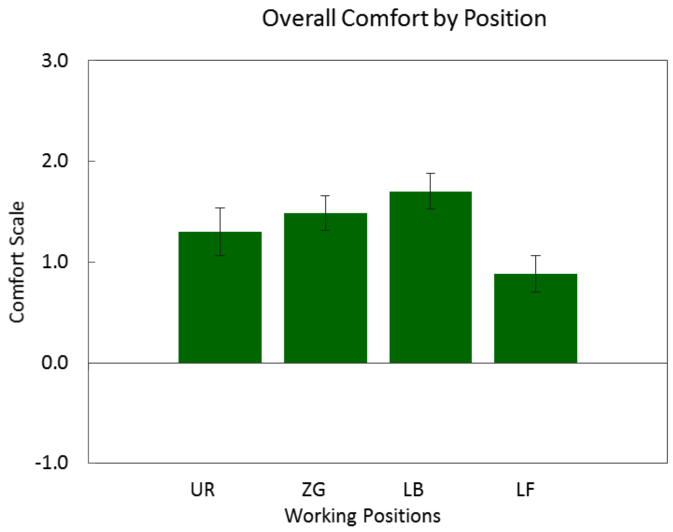


Figure 4.9 Overall comfort of each position

4.5.4 Effect of Working Position on Type of Task

Participants were asked to rate the comfort of the four working positions for the types of task to find out which position was more comfortable than the other for a particular task. The results showed that upright position was most comfortable among the other three positions for browsing and writing tasks (Figure 4.10(a)). Lean forward was the second comfortable position for these tasks. On the other hand, lean back position was most comfortable for watching and reading tasks (Figure 4.10(b)). ZG position was the second. Figure 4.10 shows the summary of mean results about the comfort rate of each position for the two groups of tasks. The vertical axis shows the number of users (0 ˜ 14) and comfort scale (0 ˜ 3) in percentage. The horizontal axis shows positions' rating for the tasks.

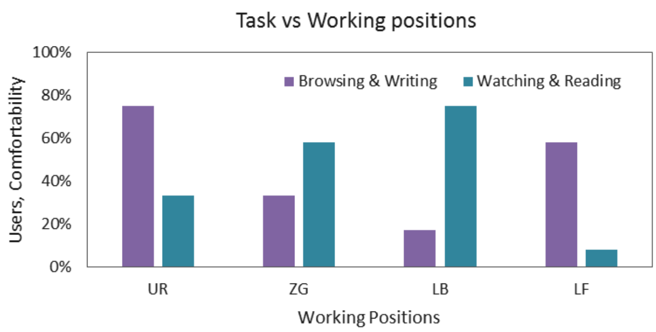


Figure 4.10 Comfortability of positions by task

4.6 Summary

Evaluation of the prototype workstation was carried out by recruiting test subjects. A subjective evaluation method, named General User Comfort test protocol, was developed. Participants rated body parts comfort on a questionnaire after working on each of the four working positions. This test was intended to assess the effects of the four working positions on the comfort of different body parts and on the overall comfort of a user. Body parts were also grouped into three body regions to identify if comfort was localized. The effects of the positions on the types of task performed were also analysed. The results showed that different working positions provided different scale of comfort for different body parts. The type of task performed had an effect on the comfort of body parts in each position. The trunk parts (lower back) and the lower extremity (like legs and feet) exhibited more comfort as the working position changed from upright position to reclined positions. This was due to the balanced support of those body parts and distribution of weight which decreased the occurrence of pressure sores around lower back and thighs. However, the comfort of upper extremity (like shoulder, arm, wrist and hand) was affected negatively when reclined. This was caused by the type of tasks that involved excessive use of keyboard and mouse. The overall comfort of users were improved by 43.3%, 49%, 56.6% and 29.3% on average during UR, ZG, LB and LF positions, respectively. However, there was no significant difference between positions except for LB and LF. The lean-back position was the most comfortable position and lean-forward position was the least comfortable position among the four positions.

Chapter 5

Comfort of the MPECW

5.1 Introduction

The effects of four selected working positions on user comfort was analysed, compared and contrasted in the previous chapter. In this chapter, the comfort of the newly designed workstation, in comparison with a standard computer setup, is discussed. The improvements in the comfort of a user working on this workstation as a personal computer setup were investigated. The demerits of this workstation were also investigated.

5.2 Methodology

The evaluation method used for this test was also subjective. As it was discussed in chapter 4, section 4.2, two types of subjective evaluations were carried out. The test protocol named Real Time User Comfort (RTUC) was used to evaluate the overall comfort of the prototype workstation and the results are discussed in this chapter.

The setup of the test equipment (prototype) for this test protocol was the same as the setup in the previous test protocol (ref. to chapter 4, section 4.2.1). However, a standard computer setup was introduced for comparison of results. The standard computer setup was the personal computer setup of each participant at their workplace.

The participants of this test protocol were also the same test subjects recruited in the previous protocol (ref. to chapter 4, section 4.2.2). This allows a consistency in results of within-subject data analysis.

5.3 Test Protocol: Real Time User Comfort (RTUC)

The same participants participated in this test protocol. The participants performed the test in a scheduled manner. Each participant was instructed to sit on the workstation and used it as if it was his/her own personal computer workstation. Participants were also instructed to perform their own tasks freely, as they would do at their own personal computer, for two continuous hours to make the experience as real as possible. They were also advised to change working positions from one position to another as necessary. The participants were free to use other working positions, including TPs, based on personal preferences. Subjects already knew how to change the position of the prototype workstation since they had performed prior tests.

After completion of the test an assessment of comfort was completed by the participants. Participants rated the comfort of different body parts by using a web-based questionnaire. Subjects also performed the same tasks for the same length of time using their personal standard setup and rated body parts comfort on the same format questionnaire.

The questionnaire for this test had three sections and a personal comment/suggestion textbox at the end. In the first section of the questionnaire, a human body outline that indicated six general body parts was presented. Each body part was associated with a comfort scale (Figure 5.1). The second section had three questions about comfort of keyboard, mouse and monitor. The seven comfort scales were: very uncomfortable, quite uncomfortable, barely uncomfortable, normal, barely comfortable, quite comfortable and very comfortable; the corresponding numbers assigned for each comfort scale were -3, -2, -1, 0, 1, 2 and 3, respectively. The baseline for comfort was “normal (0)” scale. In the third section, participants were asked to directly rate the overall comfort of the prototype setup against the standard setup (the overall comfort of the standard setup was considered “normal (0)” comfort scale).

The prototype and standard setups highlighting the main parts and design feature differences are shown in Figure 5.2.

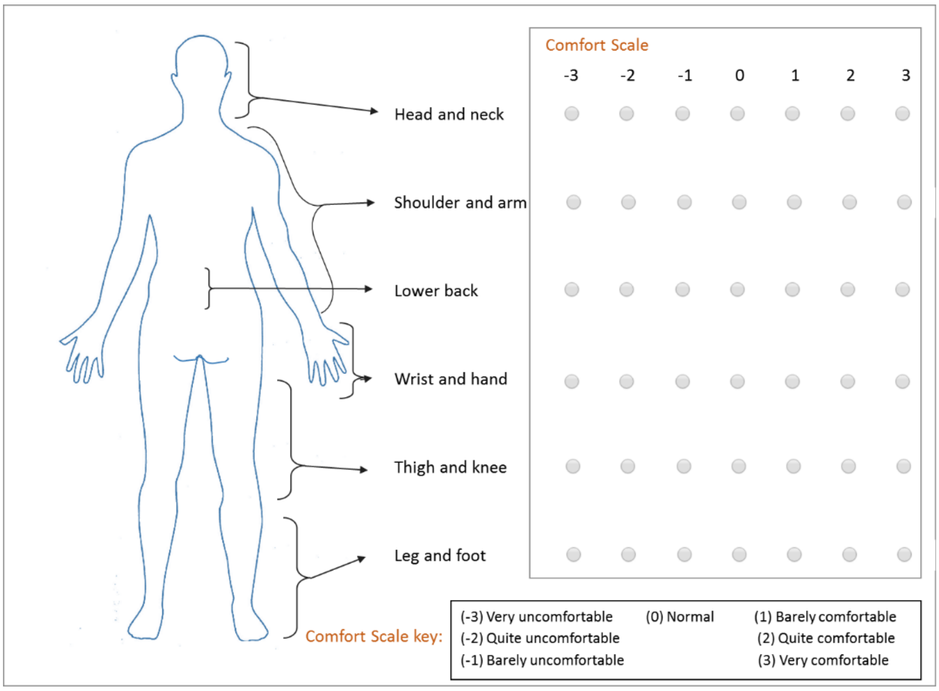
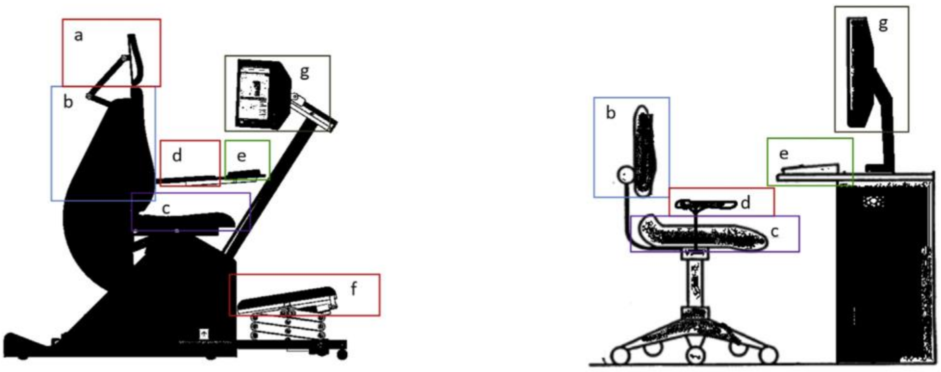


Figure 5.1 Questionnaire of RTUC test protocol



(i) Prototype (ii) Standard

Key: (a) Headrest, (b) Backrest, (c) Seat, (d) Armrest, (e) Keyboard and Mouse, (f) Footrest and (g) Monitor

Figure 5.2 Comparison of MPECW and 'standard' setup

5.4 Data Analysis

The dependent variables recorded during testing included body parts comfort (BPC) of each six body parts, comfort of the three selected workstation parts and overall comfort (OC) of the whole workstation. The body parts and workstation parts comfort rate data was directly collected by the questionnaire. The overall comfort of the workstation was also collected directly by questionnaire.

For the prototype and standard workstation setups, the median comfort value was calculated for each body part. For further study and analysis of variance and significance, the mean values, standard deviations and standard errors were also analysed.

To determine the significant difference of body parts comfort between prototype and standard workstation setups, a two-way ANOVA with repeated measures analysis[5] was performed. The two factors of analysis were 'the type of workstation' with two levels (prototype and standard) and 'the body parts' with six levels (head and neck, shoulders and arms, lower back, wrists and hands, thighs and knees, and legs and feet). Since a significant difference was found, a post-hoc t-test was conducted to determine which body parts registered significantly different comfort rate due to the type of workstation. A difference in mean comfort values was carried out to show the difference in comfort of each body part between the two workstation setups.

On the other hand, a one-way ANOVA was performed among body parts for the prototype workstation to find out the difference between each body part comfort within the prototype setup. When a significant difference was found among the body parts, a post-hoc t-test was performed to determine which body parts were significantly different from the others by correcting the significance value using Bonferroni correction method. Then, a pair-wise comparison was run to indicate which body part had the greatest impact on the overall comfort.

By calculating the mean body parts comfort of each test protocol, a comparison was made to see the difference between the standard setup, the prototype setup during GUC and the prototype setup during RTUC. Similarly, the mean overall comfort results of the workstation were compared to see the differences among the two test protocols and the standard computer setup.

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[5] A two-factor analysis of variance is used when there are two independent variables (or factors) and want to examine the effect of each of those variables independently and in interaction with each other on a dependent variable.

5.5 Results and Discussion

5.5.1 Body Parts Comfort by Workstation Type

The comfort rate of each body part and workstation part in both type of workstation setups were analysed and the median value was preferred to show the results since it is a more rounded number and there were no significant differences between the mean and median values. Figure 5.3 shows the summary of the results concerning body parts, workstation parts and overall comfort for both prototype and standard workstation setups. In the figure, the first six items on the vertical axis are body parts and the other three items are workstation parts.

Results showed that there was no discomfort during working on the prototype workstation; comfort scales for all parts were above the “normal” comfort scale (comfort scale ≥ 0). On the other hand, half of body parts (head, neck, lower back, legs and feet) exhibited discomfort (comfort scale < 0) during working on the standard setup. The headrest and armrest of the prototype improved comfort of the head, neck, shoulders and arms (comfort scale ≥ 1). The results of the lower back comfort (comfort scale = 2) indicated that the backrest of the prototype provided great comfort for the lower back, which is usually the sensitive area to feel pain during computer work. Lower extremity (thighs, knees, legs and feet) experienced high comfort (comfort scale = 2) during working on the prototype. In another evaluation of comfort of the parts of prototype (ref. section 5.5.3), the footrest registered high comfort value. It shows the results are consistent. The footrest created big difference in the comfort of lower extremity. The monitor was also comfortable (comfort scale = 2) and better than the standard setup due to its adjustability to a convenient distance from the eyes. This result may also be associated with the using of dual screens [83]-[84].

The keyboard and mouse of the prototype were “normal” (comfort scale = 0), but not more comfortable than the standard setup (comfort scale ≥ 1). Even though the users could choose their own comfortable position to get better comfort from possible position configurations, largely reclined positions were comparatively less comfortable for mouse and keyboard use. It was observed that the mouse pad area was small which decreased the comfort of mouse. The keyboard holder was also not big enough to support wrists while typing. It was also speculated that the type of keyboard and mouse used for evaluation might have affected the result since every participant used different keyboard and mouse at his/her own PC.

Participants performed their own personal work as they would do on their personal workstation. Participants were noticed changing working positions frequently which was in every 20 min, on average. Since testing of the prototype was carried out prior to this evaluation procedure, participants were able to change and control positions without difficulty. By using the advantage of manual position control, participants were noticed using more than the four working positions. For example, at LB position some participants decreased the height of the footrest so that they can bend the leg while leaning back.

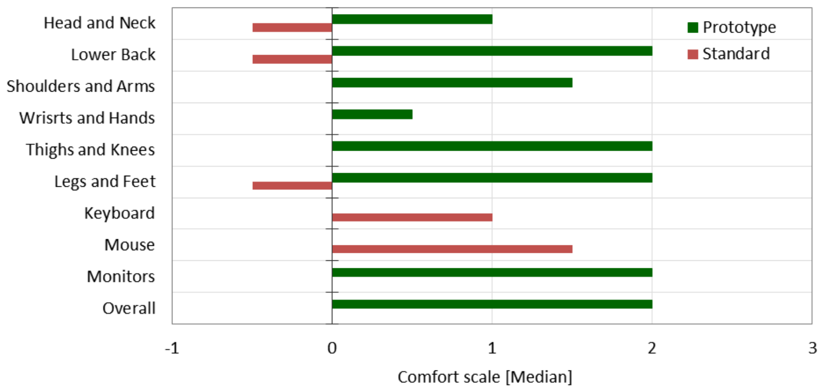


Figure 5.3 Body part and workstation parts comfort results of MPECW and 'standard' setup [median]

A statistical analysis was conducted to verify the significance difference in the results. A two-way analysis of variance revealed that there was a significant impact on comfort of body parts due to the difference between the prototype and the standard workstation setups, $F(1,156)=104.2$, $p < 0.05$. The analysis also showed that there was a significant difference between the comforts of body parts, $F(5,156) = 4.494$, $p < 0.05$. In addition, the interaction effect of workstation type and body parts was significant, $F(5,156) = 4.319$, $p < 0.05$. Figure 5.4 shows the average values of body parts comfort for both workstation setups with error bars indicating plus and minus one standard error.

The post-hoc t-test for each body part showed a significant difference between the comfort in the prototype and standard workstation setups for all body parts except wrists and hands. Working on the prototype significantly improved comfort of head and neck, $t(26) = 3.453$, $p < 0.05$, two-tailed. The comfort of shoulders and arms was also significantly improved, $t(26) = 2.88$, $p < 0.05$, two-tailed. Similarly, the prototype resulted a significant increase in comfort of lower back, $t(26) = 6.423$, $p < 0.05$, two-tailed. However, no significant effect due to prototype workstation was indicated in comfort of wrists and hands, $t(26) = 0.943$, $p > 0.05$, two-tailed. There was a significant increase in comfort of thighs and knees, $t(26) = 5.682$, $p < 0.05$; and in legs and feet, $t(26) = 6.597$, $p < 0.05$, two-tailed. (A one-way ANOVA test revealed the same significant values: for example, for the head and neck, $F(1,26) = 11.927$, $p < 0.05$; for the legs and feet, $F(1,26) = 43.513$, $p < 0.05$; however, for wrists and hands, $F(1,26) = 0.89$, $p > 0.05$.)

A difference in the mean comfort values of body parts between prototype and standard showed that lower extremity comfort was significantly improved. Table 5.1 shows the mean body parts comfort and the differences between prototype and standard workstation setups.

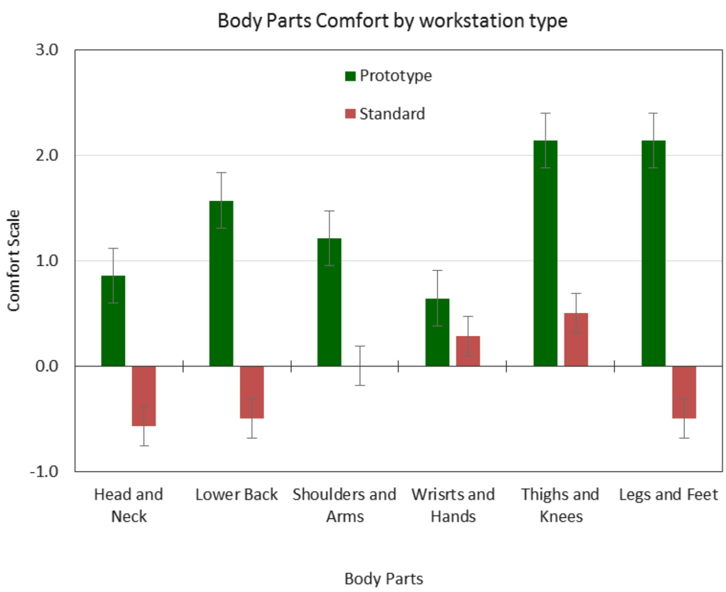


Figure 5.4 Body parts comfort by workstation type [mean]

Table 5.1 Difference in mean body parts comfort between prototype (P) and standard (S) workstation setups

	Head and Neck	Lower Back	Shoulders and Arms	Wrists and Hands	Thighs and Knees	Legs and Feet
Prototype	0.9	1.6	1.2	0.6	2.1	2.1
Standard	-0.6	0.5	0.0	0.3	0.5	-0.5
Difference (P - S)	1.4	2.1	1.2	0.4	1.6	2.6
p-value	< 0.05	< 0.05	< 0.05	> 0.05	< 0.05	< 0.05

5.5.2 Body Parts Comfort of Prototype Workstation

In the two-way analysis, it was found that there was a significant difference between body parts for both workstation setups. To determine if there was a significance difference between the comforts of the body parts in the prototype workstation, a separate one-way ANOVA was run for the data set of the prototype. The analysis confirmed that there was a significant difference, $F(5,78)=6.322$, $p < 0.05$. Figure 5.5 shows the average values of body part comfort with error bars indicating plus and minus one standard error. A post-hoc t-test was performed to determine which body parts were significantly different from the others. The significance *p*-value was corrected using Bonferroni correction method. Thighs and knees were significantly different from the head and neck, $t(26) = -6.364$, $p < 0.05$; and also significantly different from wrists and hands, $t(26) = -4.423$, $p < 0.05$. Similarly, the thighs and knees comfort was significantly better than the comfort of head and neck, $t(26) = -5.130$, $p < 0.05$; and also significantly different than wrists and hands, $t(26) = -4.05$, $p < 0.05$. However, there were no significant differences between the other pairs of body parts: for example, between head and neck and shoulders and arms, $t(26) = -0.909$, $p > 0.05$.

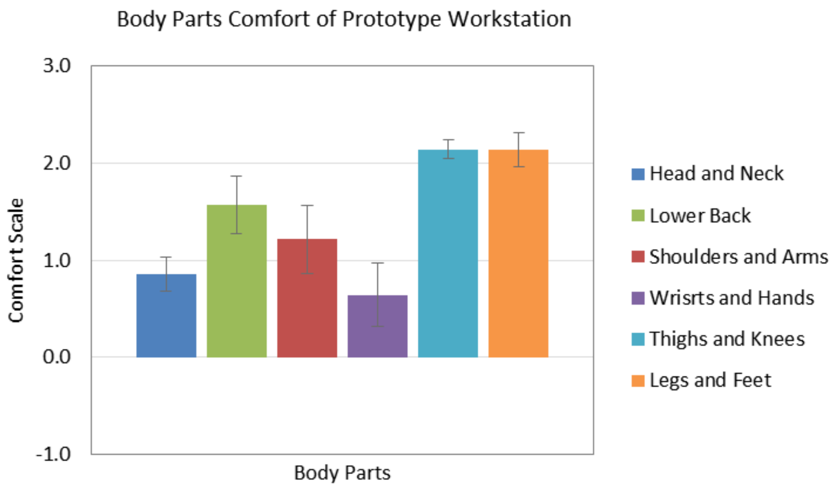


Figure 5.5 Body parts comfort significance results of MPECW

Table 5.2 Pairwise comparison of comfort of body parts

Body part(mean)	Lower Back (1.6)	Shoulders and Arms (1.2)	Wrists & Hands (0.6)	Thighs & Knees (2.1)	Leg & Feet (2.1)
Heads and Necks (0.9)	-0.71	-0.36	0.21	-1.29*	-1.29*
Lower back (1.6)		0.36	0.93	-0.57	-0.57
Shoulders & Arms (1.2)			0.57	-0.93	-0.93
Wrists and Hands (0.6)				-1.5*	-1.5*
Thigh and Knees (2.1)					0.0

*$p < 0.05$
the different in mean comfort of body parts based on prototype setup, (row) - (column)

A pairwise comparison of the mean comfort values by body parts revealed that lower extremity comfort was rated significantly better than the other body parts. The differences in mean comfort values between each body part based on the prototype setup are listed in Table 5.2.

5.5.3 Comfort of Parts of the Prototype Workstation

Participants were asked to rate the comfort of parts of the prototype by taking the standard computer workstation setup as a baseline for normal comfort. Workstation parts were divided into seven parts for comparison (Figure 5.2). Participants selected the parts of the prototype workstation that made them comfortable. The summary of the results is shown in Figure 5.6. The vertical axis shows the number of users in each percentage. The data were analysed by using a chi-square test for each workstation part. The test revealed that the results for all parts, except for the keyboard/mouse, were statistically significant, $p < 0.05$. No significant difference was found for the keyboard/mouse, $p > 0.1$. Table 5.3 shows the values of the chi-square test for each part. The headrest, backrest and footrest were significantly comfortable among the other parts. 91.7% of participants identified that the footrest increased their comfort during computer work. This indicates that the new design of footrest was the most prominent in increasing comfort. Each part made its own contribution to the overall comfort. The keyboard and mouse were not selected, as these two parts did not show improved comfort during the RTUC evaluation.

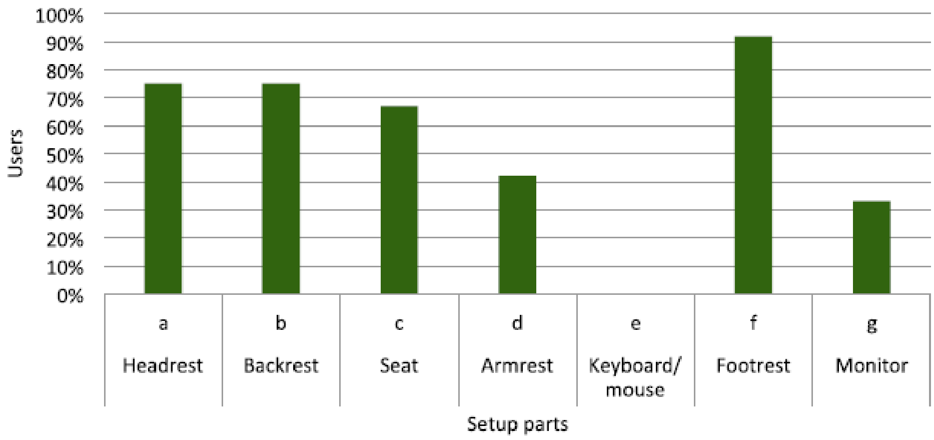


Figure 5.6 Comfort of different parts of MPECW
(0% is baseline for comfort of parts of standard setup)

.

Table 5.3 Chi-Square results of each workstation part

Work-station parts	Head-rest	Back-rest	Seat	Arm-rest	Key-board/ Mouse	Foot-rest	Monitor
X^2 value	18.118	18.118	15.556	9.333	1.037	24.266	7.636
p-value	<0.001	<0.001	<0.001	<0.01	>0.1	<0.001	<0.01

5.5.4 Comparison of Results

Two types of test protocols, GUC and RTUC, were carried out to evaluate this prototype workstation, and a standard prototype setup was included during RTUC for comparison of the results. Figure 5.7 shows the results of body parts comfort for two test protocols in comparison with standard setup evaluation results. A repeated-measures analysis revealed that there was no significant difference between results of GUC and RTUC, $F(1,156) = 0.447$, $p < 0.05$. There was also no significant impact on comfort of body parts due to the difference in test protocols, $F(5,156) = 2.154$, $p < 0.05$.

The results indicate that the impact of the prototype setup on the comfort of body parts was significant regardless of the test protocols. This implies that the comfort of the prototype setup was similar in spite of the length of time users spent or the type of task they performed on the workstation. On the other hand, as indicated in the previous analysis, the comfort of body parts is significantly improved by working on the prototype workstation. The comfort of wrists and hand was not significantly improved by the prototype workstation; however, it is still registered a better comfort than the standard workstation setup.

During GUC the evaluator operated the controller to change positions from one position to another which simulated an automatic control of positions with better accuracy. However, during RTUC, the positions were controlled manually, separately and with less accuracy towards the recommended position. The results showed that the mean comfort of all body parts was relatively closer to each other during GUC (Mean=1.3, SD=0.222) than that of RTUC (Mean=1.4, SD=0.637). Thus the automatic control of position may not essentially improve the comfort obtained by manual control; however, it can improve consistency and equivalency of comfort throughout all body parts. Moreover, it will allow any new user to work on the workstation comfortably without the need to know or worry about the type of positions or the better type of position. However, automatic position control restricts the workstation to have only four working positions. So, an automatic control along with an optional manual control was recommended for this design.

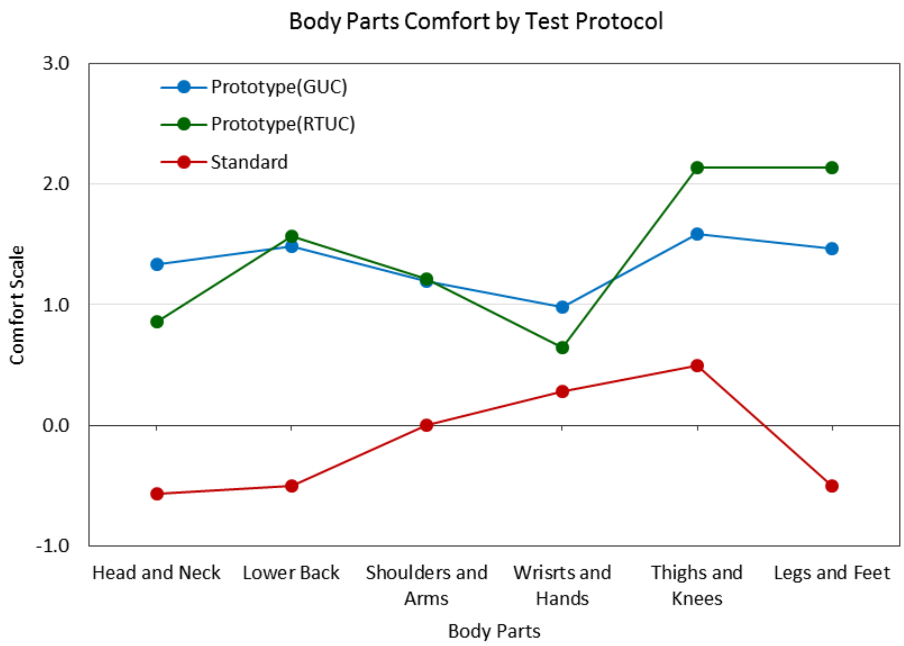


Figure 5.7 Body parts comfort comparison by test type of protocol and standard setup

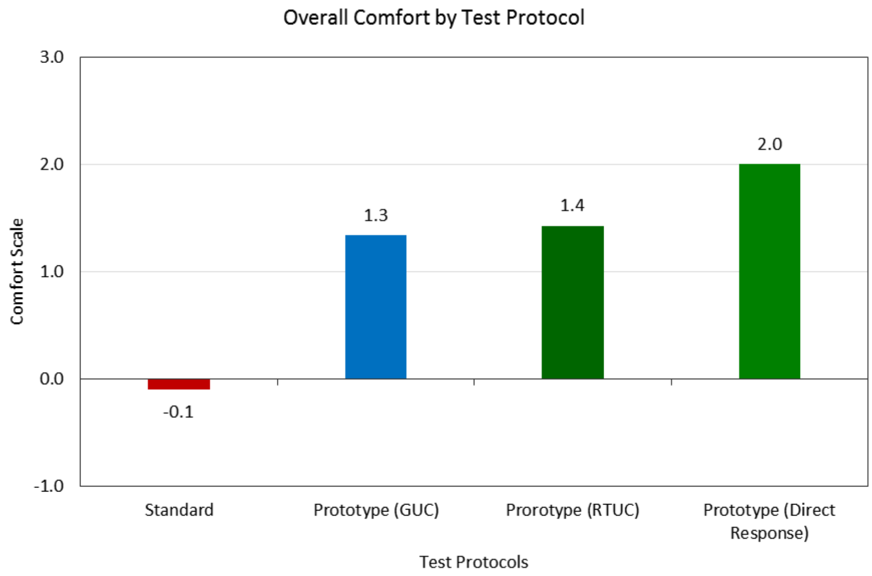


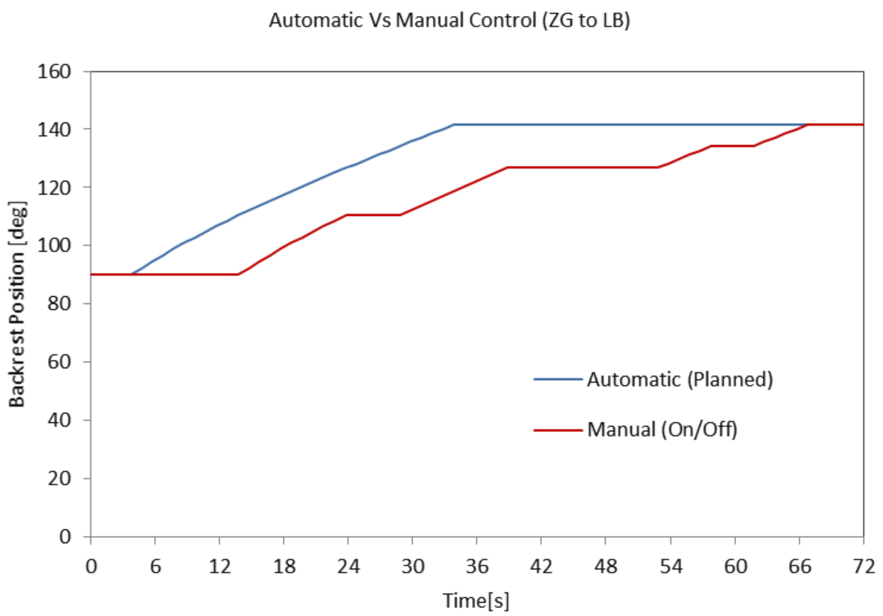
Figure 5.8 Overall comfort comparison by type of test protocol and standard setup

Participants were also directly asked in the questionnaire to rate the overall comfort of the prototype setup against the standard setup by assuming the standard setup as "normal" (comfort scale = 0). All participants rated the overall comfort of the prototype workstation as "quite comfortable" (comfort scale = 2). The participants were also asked to choose which setup they prefer to use for working at computer, and all participants chose the prototype workstation.

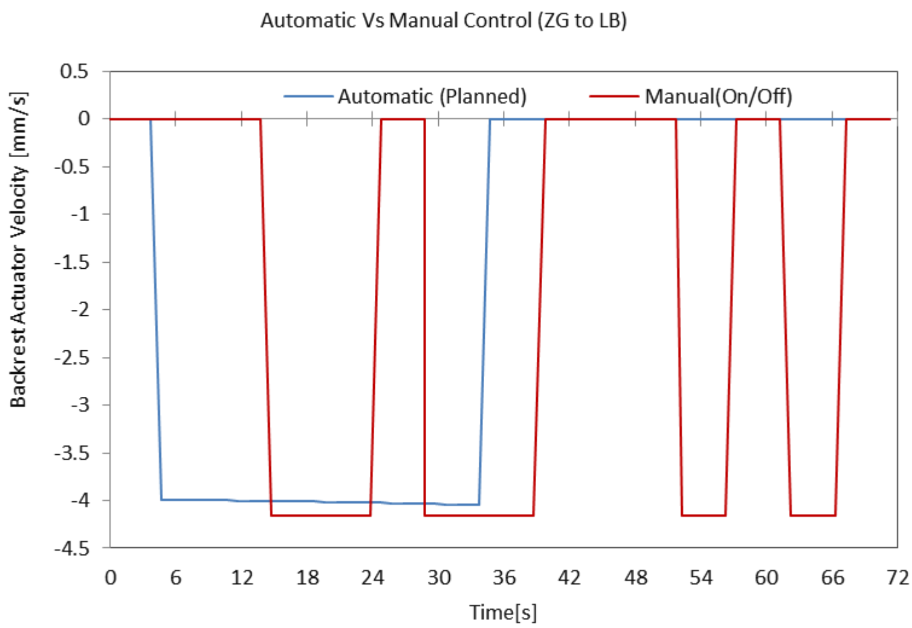
The mean overall comfort of the prototype workstation during the two test protocols is shown in Figure 5.8 in comparison with the mean overall comfort of the standard workstation setup. The result confirms that overall comfort was improved by the prototype setup (45% in average). The assumed comfort scale of the standard setup was '0' comfort scale and the results from the data showed a similar value. The direct response from the participants about the overall comfort of the prototype workstation was slightly bigger than the mean overall comfort. This can be inferred as the participants were also emotionally comfortable and satisfied.

5.5.5 Automatic and Manual Position Control

During controlling the change in position, the GUC test protocol simulated an automatic position control and the RTUC test protocol simulated a manual control. As it was discussed in previous section 5.5.4, the comfort results were relatively similar and both control methods were necessary.



(a)



(b)

Figure 5.9 Automatic and manual position control results of ZG to LB position (a) Backrest position (b) Corresponding backrest actuator velocity

In addition, the automatic position control significantly decreases the time it takes to change from one position to another position. The automatic controller had a planned actuation sequences that drove multiple actuators at the same time. As a result it decreased the total time it took to change position. However, during manual control the user not only had to change one actuator at a time, but also decide the sequence randomly by observation. So, the time it takes will be the sum of the time it took for every moved actuator. In actual experiment, it even took more time since there was a time spent for sequence decision and position checking. As an example, Figure 5.9 shows the results of the backrest position and the corresponding actuator velocity during automatic and manual control of position change from ZG to LB position. The time it took during automatic control was 34 seconds, however it took 71 seconds (more than two times) during manual control.

5.5.6 Effect of User Height on Setting Working Positions

The values of all the parameters that control the setting of each position were specified based on the average height of 170cm. However, when controlling the position manually during experiment, it was noticed that all users didn't essentially set the values of all parameters to the specified values for each working position. Few parameters were affected by the height of users. The values of θ_b, θ_s and θ_f were constant for all height of users at each position; these three parameters didn't change at any position as height of user changed. However, the values of θ_m, d_m, d_d and d_h were changed as height of user changed at each position. These parameters were fine-tuned to complement the fixed parameters by manual control based on user's personal feeling, ergonomic guidelines and proportionality.

To elaborate the effect of user height on setting each working position, the change of parameters with height at lean-back position is shown in Figure 5.10. The result shows that the strokes of the two parameters, $d_d = f(s_{fd})$ and $d_m = f(\,s_{mh})$, changed when the height of users changed at lean-back position. Even though the relation seems rather random, it can be approximated as a linear relationship between the stroke of the parameter and the height of the user. Thus, the stroke of a parameter for a specific height of user at a given working position can be obtained by a linear equation given by:

$$S_{i,j}^{H} = mH - cS_{i,j} \tag{5.1}$$

where

$S_{i,j}^{H}$: Corrected stroke of the *i* parameter for user height *H* at *j* position
m: Slope
H: Height of a user
c: correction factor
$S_{i,j}$: Stroke value of the *i* parameter at *j* position (control value)
i = { *ma, mh, fd, fh*}
j = {*UR, ZG, LB, LF*}

The above equation 5.1 can be used to correct the control parameter values according to the height of a user for automatic control. However, the manual control comes in handy to adjust (fine-tune) these values manually depending on a personal preference of a user. So, a combination of automatic and manual control system was recommended for this workstation design.

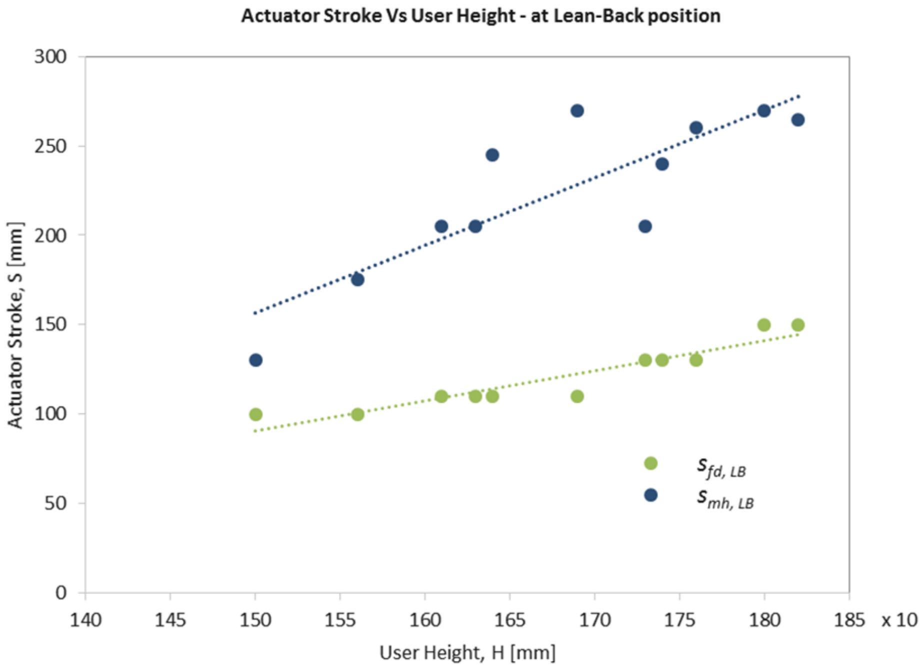


Figure 5.10 Effect of height on parameters of working positions

5.6 Summary

Evaluation of the prototype workstation was carried out by recruiting test subjects. A subjective evaluation method, named Real Time User Comfort test protocol, was developed. Participants rated body parts comfort on a questionnaire after working on the MPECW for two continues hours; and again after working on a standard setup. This test was intended to evaluate the comfort of different body parts and the overall comfort of users during working on the prototype and compare the results with working on a 'standard' workstation setup. The test also included the assessment of seven main workstation parts that had a major contribution to the overall comfort. The results showed that different body parts exhibited different level of comfort. However, there was a significant improvement in the comfort of almost all body parts, $p < 0.05$, except wrists and hands ($p > 0.05$), compared to 'standard' setup. Similarly, comfort of parts of the workstation were significantly different from comfort of parts of a standard setup, except for keyboard and mouse. On the other hand, comfort results of the two test protocols were not significant different; which also implies neither the type of control nor the length of time had significant impact on comfort this prototype. But, automatic control provided consistent and equivalent comfort results, in addition to smooth and quick position changes. The overall comfort of users was significantly improved by working on the prototype workstation, $p < 0.05$. On the other hand, the comfort of lower extremity was significantly improved, and it was due to the comfort of footrest.

An automatic position control system (used during GUC) and a manual position control system (used during RTUC) were compared. Automatic control delivered smooth and quick position changes, and resulted a relatively equivalent comfort across body parts; but, it restricted the workstation to only four working positions. A manual control was suitable to work on many alternative working positions and fine-tune working position in proportion to personal height. So, a combined control system was recommended for this workstation design.

Chapter 6

Conclusions

A novel concept of computer workstation which enables users work in multiple alternative positions was designed by implementing ergonomics principles. This study is intended to increase comfort of computer work for people who spend most of their work-time seated at their computer, in work environments that involve heavy computer use, since discomfort is bad for health and reduces productivity in the long run.

The newly designed Multi-Position Ergonomic Computer Workstation had 19DOFs, where 7DOFs were controlled by linear actuators that change the position parameters of the backrest, the seat, the monitor-post and the footrest. The workstation was designed to accommodate a population from 5th percentile female to 95th percentile male human size. The maximum safe load it can carry was 96 kg of user body mass. Among multiple possible alternative positions, four working positions were selected: namely, upright, zero-gravity, lean-back and lean-forward positions. A prototype was also developed.

The mechanisms were governed by seven parameters, four angular and three linear, which were directly associated with the corresponding strokes of each of the seven actuators. The parameters were defined in the function of the corresponding strokes using direct kinematic equations. The position change sequences between the four working positions were determined by defining transitional positions that allow interference-free and comfortable position changes. The control system estimates the current position from the values of the parameters and sets new parameters corresponding to the goal position.

Evaluation of the prototype workstation was carried out by recruiting test subjects. A test protocol, named General User Comfort test, was used to assess the effects of four selected working positions on the comfort of different body parts and on the overall comfort of a user. Body parts were also grouped into three to identify if comfort was regional, and the effect of the positions on the type of task performed was also analysed.

Another the test protocol, named Real Time User Comfort, was conducted to evaluate the comfort of different body parts and the overall comfort of users during working on the prototype and compare the results with working on a 'standard' workstation setup. The test also included the assessment of seven main workstation parts that had a major contribution to the overall comfort.

The findings from this study can be concluded as follows.

- The posture control system could achieve a smooth transition from the current position to the goal position.
- The longest time to change from one position to another was less than a minute (53 seconds) and the shortest time was 15 seconds.
- Different working positions provided different scale of comfort for different body parts. The type of task performed had an effect on the comfort of body parts in each position.
- The middle and lower extremity exhibited more comfort as the working position changes from upright position to reclined positions. However, the comfort of upper extremity (like shoulder, arm, wrist and hand) was affected negatively when reclined.
- There is a significant impact on overall comfort due to working positions, $p < 0.05$. Overall, the lean-back position was the most comfortable position and lean-forward position was the least comfortable position among the four positions.
- There was a significant improvement in the comfort of almost all body parts, $p < 0.05$, except wrists and hands ($p > 0.05$), compared to 'standard' setup. Especially, the comfort of lower extremity was significantly improved, and it was due to the comfort of footrest. Similarly, comfort of parts of the workstation were significantly different from comfort of parts of a standard setup, except for keyboard and mouse.
- The overall comfort of users was significantly improved by working on the prototype workstation, $p < 0.05$.
- Automatic control delivered smooth and quick position change, and resulted a relatively equivalent comfort across body parts; but, it restricts

the workstation to only four working positions. A manual control was suitable to work on many alternative working positions and fine-tune working position in proportion to personal height. So, a combined control system was recommended for this workstation design.

Limitations and Future Outlook

This research targeted users who spend most of their work-time seated at their computers and, generally, did not move a lot away from their computer. This workstation is not ideal for people who move away from their computer or sit and stand a lot. To get off the workstation, the position of the workstation have to be at UR position. The workstation did not have a wide area that can be comparable with table. Thus, it is not also ideal for users who also do a lot of paper work while working on computer.

In the current design, an ideal user changes working positions based on personal preference. A user may change working position when the user feels discomfort at the current position or want to change to another position for different kind of computer task. In the future work, pressure sensors can be introduced to measure and monitor the pressure distribution around sensitive body parts. If there is a high pressure area, non-uniform distribution or hot spot, it may create fatigue in the body that can lead to discomfort over time. Based on this pressure mapping data, an intelligent system of the workstation may be developed that can locate the hot spot and calculate the time it takes to lead to pain. Then the system may determine a different working position and/or body posture to avoid this hot spot and recommends to the user. With the confirmation of the user to change to the new working position, the system may trigger the synchronized actuators to change to the new position automatically. The system again may check the new pressure distribution and assist the user in real-time.

On the other hand, the automatic position control has to be initiated by the user to change from one position to another based on personal preference. In the evaluation, the relation between type of task and working position was shown. However, we didn't develop a mechanism to automatically change working position based on the type of task the user is performing. A system that can observe the type of task the user is performing can be developed and be implemented to automatic change the position to a more comfortable position for the observed specific task. By implementing pressure sensing and observatory systems, the workstation can be enhanced to an intelligent workstation that fully interacts with the user and provide optimum working position for improved comfort, performance, productivity and concentration and relaxation for all kind of computer tasks.

Even though increasing comfort reduces risk of RSI and increases productivity, too much comfort may make the user feel sleepy and lose concentration. On the contrary, if there is discomfort, not only productivity decreases but also pain grows which may lead to RSI in long term. A further experiment by directly evaluation productivity can be conducted focusing on optimizing comfort and productivity. Other evaluation like safety and adaptability can also be conducted.

The participants during evaluation were university students and that has limited not only the range of age but also the diversity in profession & experience of participants. Including participants who are older and from other professions that involve long time computer work would reveal a more comprehensive results. On the other hand, it would be interesting to test for aging societies, like Japan, by sampling older working people since they would have specific body issues related to their age. We may find other interesting results by conducting different experiments for specific age group, for specific professions and for specific computer tasks. We evaluated the relation between the type of task and comfortability of working positions; but a further objective experiment, like typing performance, may show more detail characteristics of each position for a specific task.

A different experiment with a different objective can be conducted for long time (for e.g. a month) by recruiting only few participants to assess the long term perspective of this system since pain and ache do not happen in one day, but grow thorough time

The developed mechanism and principle can be applied for other work environment that involve sitting for long time. So, we strongly believe that this workstation can be used as an apparatus to conduct similar and individual researches.

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List of Publications

Academic Journals

1) Workineh Sisay A. and Yamaura Hiroshi (2016) Multi-Position Ergonomic Computer Workstation Design to Increase Comfort of Computer Work, Intl. Journal of Industrial Ergonomics 53, p1-9. *Chapter* 5

2) Workineh Sisay A. and Yamaura Hiroshi (2015) Effects of multiple working positions on user comfort: A study on multi-position ergonomic computer workstation, Elsevier, Procedia Manufacturing 3, p 4792-4799. *Chapter* 4

3) Workineh Sisay A. and Yamaura Hiroshi (2014) Design of 3DOF Footrest to Increase Comfort of Computer Workstation, Applied Mechanics and Materials, Vol. 704, p113-117. *Chapters* 2 & 3

International conferences

1) Workineh Sisay A. and Yamaura Hiroshi (July 2015) Effects of multiple working positions on user comfort: A study on multi-position ergonomic computer workstation, 6th Intl conf on Applied Human Factors and Ergonomics, Las Vegas, USA.

2) Workineh Sisay A. and Yamaura Hiroshi (Oct. 2014) Design of 3DOF Footrest to Increase Comfort of Computer Workstation, 3rd Intl conf on Mechanics and Control Engineering, Asheville, USA. (Best Presentation Award).

3) Workineh Sisay A. and Yamaura Hiroshi (July 2014) Evaluation of Comfort of Multi-position Ergonomic Computer Workstation, 5th Intl conf on Applied Human Factors and Ergonomics, Krakow, Poland.

Domestic conference

1) Workineh Sisay A. and Yamaura Hiroshi (Aug. 2013) Design of Multi-position Ergonomic Computer Workstation, Dynamics and Design Conference 2013, Fukuoka, Japan.

Workshops

1) Workineh Sisay A. and Yamaura Hiroshi (Oct. 2013) The Asia-Oceania Top University League on Engineering 2013, Chulalongkorn University, Bangkok, Thailand.

2) Workineh Sisay A. and Yamaura Hiroshi (Aug. 2013) 5th multidisciplinary international student workshop 2013, Tokyo Institute of Technology, Tokyo, Japan. (One of Top 5 Presentation)