The ergonomic assessment of two different pipette models and their effects on biomechanical, performance, and subjective outcomes.

By

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Thesis

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Abstract

While laboratory workers are essential in many industries, they are also at a high risk of developing musculoskeletal disorders (MSDs). Manual pipetting has been identified as the leading cause of MSDs in laboratories because it exposes operators to high forces, repetition, static muscular loading, and awkward wrist postures for prolonged periods. The main contributors to the high risk associated with manual pipetting are the design of manual pipettes and how they are used.

A laboratory-based study was conducted to assess and compare the biomechanical, subjective, and performance responses of an ergonomically designed pipette model to those of a traditional model. In a simulated laboratory workstation, 20 individuals performed 40 repetitions of pipetting tasks using each pipette model. Dependent variables consisted of muscle activity (of the Abductor Pollicis Brevis, Opponens Pollicis, Extensor pollicis longus, Abductor pollicis longus, Extensor pollicis brevis, and brachioradialis muscles), wrist postures, time to task completion, perceived muscular exertion (measured using the Borg RPE scale), perceived comfort and usability, and user preference.

The results revealed that an ergonomic modification to pipette design has some effect on biomechanical and subjective outcomes. The ergonomic model significantly reduced muscular loading of the Opponens pollicis, and Abductor pollicis brevis muscles. The ergonomic model also reduced radial deviation and was associated with better subjective responses, while the time to task completion did not change. This study found that an ergonomic modification to pipette design can improve user comfort and well-being without compromising performance.

Overall, the findings emphasize the importance of addressing pipette design to reduce the MSD risk associated with manual pipetting, and the necessity for a user-centred approach to tool design.

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Chapter 1

Introduction

Context of the study

Laboratory scientists and technicians are professional workers skilled in conducting research and performing diagnostic, analytical, technical, and mechanical tests in laboratories (El-Helaly et al., 2017). These professionals form part of a diverse workforce that includes pharmacists, researchers, medical laboratory technologists, and clinical laboratory technologists, among others, and play an integral role in various national and international work structures such as healthcare, medicine, production, food processing, biotechnology, electronics, agriculture, and so on (Unyi & Asato, 2015; Canadian Centre or Occupational Health and Safety, n.d.). In the United States, approximately 337 800 clinical laboratory technologists and technicians were registered and employed in 2019 (Garcia et al., 2021), while in South Africa, over 11 000 medical laboratory technicians and scientists (including practitioners, interns, and students) were registered with the Health Profession Council of South Africa in 2018 (Ellapen et al., 2021). Of these, the National Health Laboratory Service (NHLS), a diagnostic pathology service, employs approximately 7000 workers in 260 laboratories across the country, providing laboratory and other public health services to 80% of the population through a network of laboratories (*National Health Laboratory Service*, n.d.). The COVID-19 pandemic, in particular, emphasized the importance of laboratory work, as laboratory workers performed COVID-19 testing, diagnosis, and analysis on millions of samples. Gohar & Nowrouzi-Kia (2022) mention that, in Canada, medical laboratory personnel collected and analysed over 13 million COVID-19 tests. In South Africa, the National Institute for Communicable Diseases reported that from the 1st of March 2020 to the 13th of July 2021 alone, 3,4 million COVID-19 positive tests had been conducted and processed in laboratories (*National institute for communicable diseases*, n.d.). The statistics mentioned above highlight the importance of laboratory workers, specifically in healthcare; however, laboratory scientists and technicians are found in various other work settings.

Laboratory personnel are exposed to a variety of occupational hazards, including biological hazards (such as disease-causing micro-organisms and bacteria), toxic and dangerous gases and chemicals, physical hazards (radiation and noise), as well as ergonomic hazards (such as repetitive motions, and high forces) (Holm et al., 2016; Joseph & Joseph, 2016). Exposure to one or more of these hazards put laboratory workers' health at risk and can result in unfavourable outcomes such as injuries, illnesses, and even death (Nasrallah et al., 2022). The Occupational Safety and Health Administration (OSHA) reports that laboratories, especially academic laboratories, are 11 times more dangerous than other industrial environments, emphasizing the high risk associated with laboratory work and the importance of safety within this profession (Lestari et al., 2019).

Among the many occupational risks that laboratory workers are exposed to, ergonomic risks, particularly the risk of Musculoskeletal Disorders (MSD), contribute significantly to the prevalence of laboratory injuries. This is because routinely performed laboratory tasks such as manual pipetting, microscopy, and micromanipulation expose workers to ergonomic risk factors such as high forces, high repetition, and awkward postures, which result in micro-traumas that contribute to the cumulative risk for MSD development in workers (Hoskins & Erickson, 1998; Rempel et al., 2008; Unyi & Asato, 2015; Penkala et al., 2018). Furthermore, work stresses such as time constraints to produce results, accuracy demands inherent in laboratory tasks, organisational structures, and individual factors increase the MSD risk placed on laboratory workers (Penkala et al., 2018). As a result, laboratory work has been associated with a high incidence of musculoskeletal disorders (MSDs), especially those affecting the upper limbs (McGlothin & Hales, 1996; Penkala et al., 2018). According to Penkala and colleagues (2018), the prevalence of laboratory work-related musculoskeletal problems in Iran and India was reported to range from 72% to 80%. Penkala et al. (2018) also investigated the prevalence of MSDs among medical science students and discovered that more than a third of the students experienced work-related musculoskeletal problems early in their laboratory-based training. They reported that the common sites for musculoskeletal problems among medical science students during laboratory tasks were the lower back (30%), neck (24%), and upper back (21%), and that these were a result of awkward and prolonged working postures with static loads on muscles (Penkala et al., 2018). In addition, McGlothin & Hales (1996) investigated the prevalence of upper limb MSD complaints among research technicians working in production laboratories and discovered that 47% of these workers had work-related upper limb musculoskeletal complaints. The hand was the commonly affected area (40% of workers), followed by the elbow (19%), shoulder (16%), and neck (14%).

These MSDs are often associated with pain, discomfort, reduced range of motion, and inflammation and can impair one's ability to do work (AlNekhilan et al., 2020). Moreover, MSDs in the workplace are linked to absenteeism, disabilities, loss of productivity, and compensation costs (Erick & Smith, 2011; Sirajudeen et al., 2018). Given that laboratory work typically requires precision and accuracy, pain and discomfort resulting from MSDs reduce the affected laboratory workers' ability to perform work precisely and accurately, reducing the quality of work and jeopardizing their job security (Rainin, 2016). The disruption of laboratory work and services due to MSDs can have negative implications on the operation of overall work systems; for example, reduced quality of work in medical laboratories can result in misdiagnosis and loss of productivity in healthcare systems.

The frequent use of manual pipettes in laboratories has been linked to several work-related musculoskeletal disorders in laboratories (Hoskins & Erickson, 1998). Manual pipetting is an essential part of laboratory work that involves the use of a mechanised thumb-operated hand tool (a pipette) to precisely transfer small volumes of fluid from one container to another (Lintula & Nevala, 2006; Lu et al., 2008; Holm et al., 2016). These pipettes are used for prolonged periods over a work shift and expose pipette operators to various risk factors such as static muscle loading, repetition, awkward postures, high forces, and non-neutral wrist postures, which affect the neck and upper limbs (Unyi & Asato, 2015). According to Hoskins & Erickson (1998), the main reason pipetting poses a high risk of injury and MSD development is due to the design of pipettes and how they are used. Features of manual pipettes such as high plunger forces, poor handle design, and the axial grip have been associated with increased muscular strain, awkward postures, increased user discomfort, and in turn, an increased risk of repetitive strain injuries common to pipette users such as Carpal Tunnel Syndrome, and De Quervain's tenosynovitis (Lu et al., 2008; Sormunen & Nevala, 2013; Rainin, 2016).

Several manufacturers that produce different mechanical pipette models with varying features depending on the technical requirements. According to David & Buckle (1997) and VistaLab Technologies (2001), these manufacturers generally produce mechanical pipette models that conform to the traditional pipette design which includes an axial grip, dagger-like thumb push-button, and spring-loaded pipette functions requiring manual force for pipette operation. These pipette features are associated with various ergonomic concerns, such as excessive force for tip insertion and ejection, high thumb forces for aspiration and dispensation, high repetition, awkward wrist, elbow, and shoulder postures during operation, as well as high grip forces and reduced hand strength attributed to the pipette handle shape (Fredriksson, 1995; Erickson & Woodard, 2001; VistaLab Technologies, 2001; Costello, 2005; Rempel et al., 2008; Sormunen & Nevala, 2013; Holm et al., 2016). As a result, the design of axial pipette models is associated with increased muscular strain, awkward postures, and an increased risk of musculoskeletal disorder development among pipette users (VistaLab Technologies, 2001; Lintula & Nevala, 2006; Sormunen & Nevala, 2013).

Sormunen & Nevala (2013) highlight that the incidence of MSDs among laboratory workers can be reduced by minimising the physical risk factors attributed to pipette design and redesigning problem features. This can be achieved by applying ergonomic principles to tool design, whereby users and their capabilities are considered. The application of ergonomics into tool design can reduce the risk of injury, increase comfort and productivity, alleviate physical and psychosocial stress, as well as improve worker well-being (Unyi & Asato, 2015; Rainin, 2016). In addition, Edgren et al. (2004) mention that hand tools, such as pipettes, should be designed to optimize tool dimensions relative to the hand anthropometry and capabilities of the users to reduce the strain placed on users during tool use.

Statement of the Problem and purpose of the study

It is evident that current mechanical pipette models are associated with a high risk of MSD development as a result of their design and usage. Features of such pipettes contribute to the muscular loading, postures, and comfort of users, and in turn contribute to the cumulative risk of MSD development associated with pipetting. The application of ergonomic principles in the design of pipettes and their features can help reduce this risk and the incidence of MSDs among laboratory workers.

As a result, the purpose of this study was to compare the effects of an ergonomically designed pipette model to that of a traditional mechanical pipette on biomechanical responses, subjective responses, and performance indicators. This was done do assess whether the ergonomically designed pipette can reduce the risk factors associated with manual pipettes. This study's results can help improve ergonomic safety within laboratories, by promoting the implementation of ergonomics in pipette design.

Research hypothesis

Given that ergonomics aims to reduce MSD risk factors and improve user wellbeing and performance, it was hypothesized that an ergonomically designed pipette model would reduce biomechanical strain and improve performance and subjective responses in comparison to a traditional pipette model.

Biomechanical responses included muscle activity, wrist postures, and wrist range of motion. Performance responses included time to task completion, and subjective responses included measures of perceived muscular exertion, comfort, and usability.

Statistical hypothesis

The following hypotheses highlight the expectations that an ergonomically designed pipette model would have on biomechanical, performance, and subjective responses.

<u>Biomechanical responses</u>

The null hypothesis states that biomechanical responses would be the same between the traditional pipette model and the ergonomic pipette model.

H_0: $\mu_{\text{biomechanical responses traditional pipette model}} = \mu_{\text{biomechanical responses of ergonomic pipette model}}$

The alternative hypothesis proposes that there will be a difference in biomechanical responses between the traditional pipette model and the ergonomic pipette model.

Ha: $\mu_{\text{biomechanical responses traditional pipette model}} \neq \mu_{\text{biomechanical responses ergonomic pipette model}}$

Where: Biomechanical Reponses include muscle activity, wrist postures, and wrist range of motion.

Performance responses

The null hypothesis states that performance will remain the same between the traditional pipette model and the ergonomic pipette model.

H_0: $\mu_{\text{performance responses traditional pipette model}} = \mu_{\text{performance responses ergonomic pipette model}}$

The alternative hypothesis states that there will be a difference in performance between the traditional pipette model and the ergonomic pipette model.

Ha: $\mu_{\text{performance responses traditional pipette model}} \neq \mu_{\text{performance responses ergonomic pipette model}}$

Where: performance responses include time to task completion.

Subjective responses

The null hypothesis proposes that subjective responses would be the same between the traditional pipette model and the ergonomic pipette model.

H_0: $\mu_{\text{subjective responses traditional pipette model}} = \mu_{\text{subjective responses ergonomic pipette model}}$

The alternative hypothesis proposes that subjective responses would differ between the traditional pipette model and the ergonomic pipette model.

Ha: $\mu_{\text{subjective responses traditional pipette model}} \neq \mu_{\text{subjective responses ergonomic pipette model}}$

Where: Subjective responses include measures of perceived muscular exertion, and perceived comfort and usability of pipette features.

Chapter 2

Review of related literature review

This chapter will define pipetting, explain the MSD risk associated with repetitive manual pipetting, and discuss potential interventions to mitigate this risk. The first section delves into pipetting, followed by the various types of pipettes. The third section will cover Musculoskeletal disorders, Upper limb MSDs, and RSIs associated with pipetting, and the fourth section will address the risk factors contributing to MSD development. The fifth section explores the mechanisms and components of tool design and the risk factors attributed to pipette use. The need to address pipette design through ergonomic interventions, and comparative studies exploring the effect of pipette design on physical, individual, and psychosocial aspects follows in the sixth section. The seventh section consists of techniques for assessing the risk associated with manual pipetting, and the last section is a market analysis of the different pipette models produced by various manufacturers.

2.1 Definition of pipetting

Laboratory work requires precise and repetitive upper limb movements which include the use of pipettes to measure small volumes of liquid (Holm et al., 2016). Pipettes are thumb-operated hand tools used for the precise and accurate aspiration and dispensation of small amounts of fluid from one container to another. They also prevent sample contamination during fluid transfer (Lintula & Nevala, 2006; Holm et al., 2016; Kim et al., 2020). These tools function by depressing a spring-loaded plunger which creates a suction force above the chamber that holds the fluid, and then selectively releasing the plunger to aspirate or dispense a given volume (Kim et al., 2020).

According to Lintula & Nevala (2006), laboratory workers use pipettes intermittently for short to extended periods performing monotonous, repetitive actions throughout their work shift. Pipetting often involves short work cycles, high repetition, concentration, accuracy, and precision and is sometimes done under time pressures due to the time-sensitive nature of the experiments and analysis methods used (Fredriksson, 1995; Lee & Jiang, 1999). In a single pipetting cycle, pipetting steps include tip insertion, fluid dispensation, and tip ejection (see Figure 1, page 8). These actions are repeated continuously several hours a day and several days a week and place workers at a risk of developing Repetitive Strain Injuries and Musculoskeletal disorders (Hoskins & Erickson, 1998).

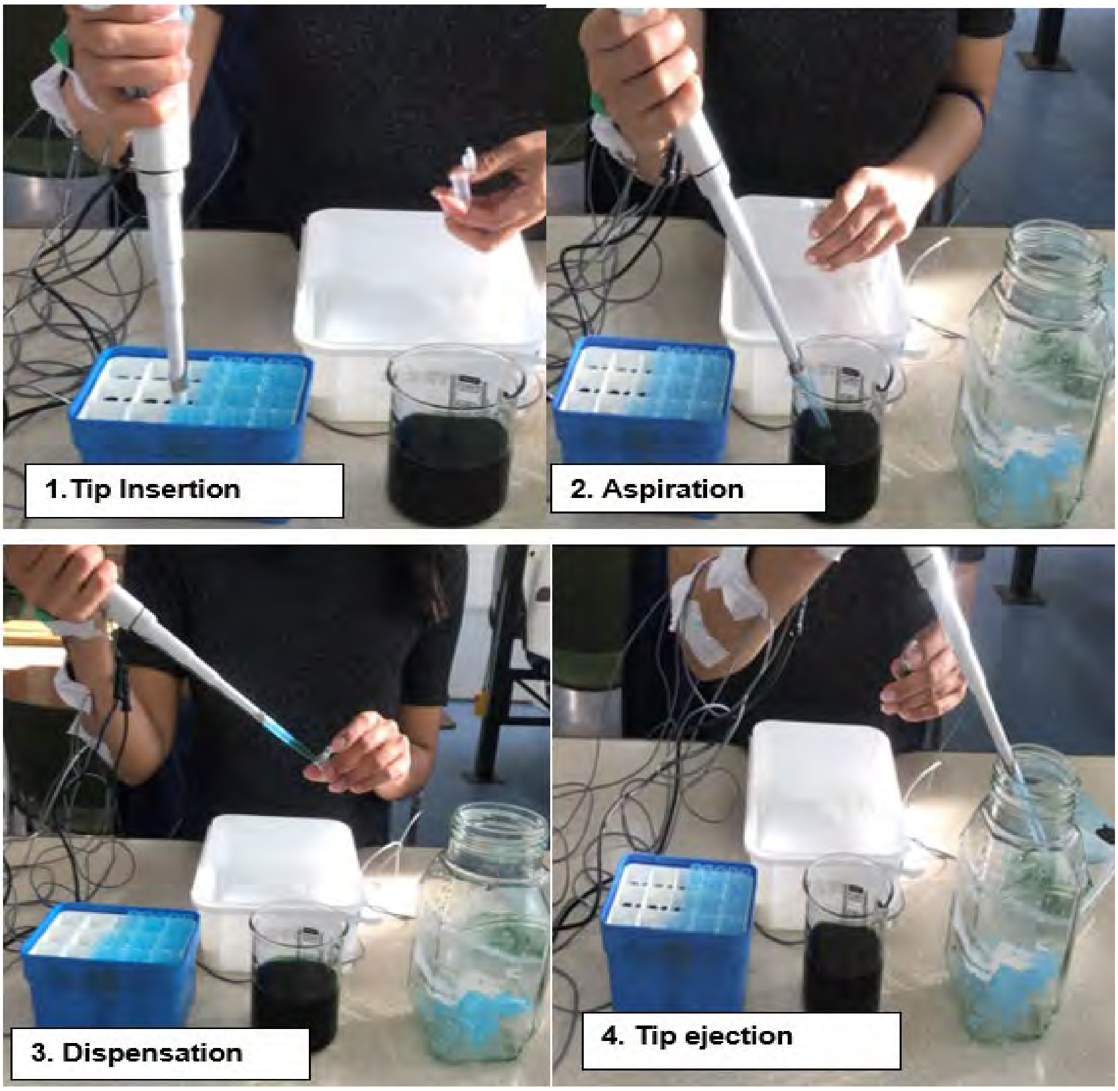

Figure 1: Pipetting steps - Tip insertion, fluid aspiration, fluid dispensation, and tip ejection performed using a traditional mechanical pipette model.

2.2 Types of pipettes

According to Costello (2005), pipettes/pipettors have evolved from mouth-operated glass tubes to being manually or automatically operated. Manual or mechanical pipettes are mechanized plunger-operated pipettes that require high thumb, finger, or palm forces (depending on the pipette design) to activate pipette functions (Holm et al., 2016; Kim et al., 2020). Thumb-operated pipettes are the commonly used pipette models in several laboratories. The thumb, during manual pipetting, is responsible for controlled fluid aspiration, dispensation, tip ejection, plunger manipulation, and emptying pipette cabinets (Wu et al., 2012; Erickson & Woodard, 2001). Most mechanical pipettes are single-channelled (they consist of a single passageway for the movement of fluid) and elongated/ axial in shape, and have an insertion point for a disposable tip (Costello, 2005) (see Figure *2*, page 10). The design of standard mechanical pipettes includes a spring-loaded plunger located at the top of the barrel, which is controlled by the downward pressure of the thumb for aspiration and dispensation of liquids (Lu et al., 2008; Holm et al., 2016).These pipettes typically have two buttons, the first is for the aspiration and discharging of fluid, and the other trigger is for the ejection of the tip (David & Buckle, 1997; Lu et al., 2008). The volume of the liquid to be dispensed is set by manually rotating the plunger dial or by depressing operating buttons (depending on the design of the pipette), and the volume setting is shown on the digital display found within the body of the pipette (David & Buckle, 1997; Lu et al., 2008). During pipetting, the pipette is held in a dagger dip with the fingers flexed around the barrel/body, which is pushed against the thenar eminence, and the distal phalanx of the thumb is held flexed to push the plunger (see Figure *2*, page 10) (David & Buckle, 1997).

In contrast, automatic/electronic pipettes are controlled by an inbuilt electromotor which decreases the pressure required to activate pipette functions and the repetitive motion associated with manual pipetting (see Figure *2*, page 10) (Burt, 2016; Holm et al., 2016). In addition, Burt (2016), mentions that Nevala-Puranen and Lintula investigated the ergonomics and usability of electronic and manual pipettes and found that electronic pipettes were associated with lower muscular strain of the upper extremities, lower thumb strain, and better perceived features of usability in comparison to mechanical pipettes.

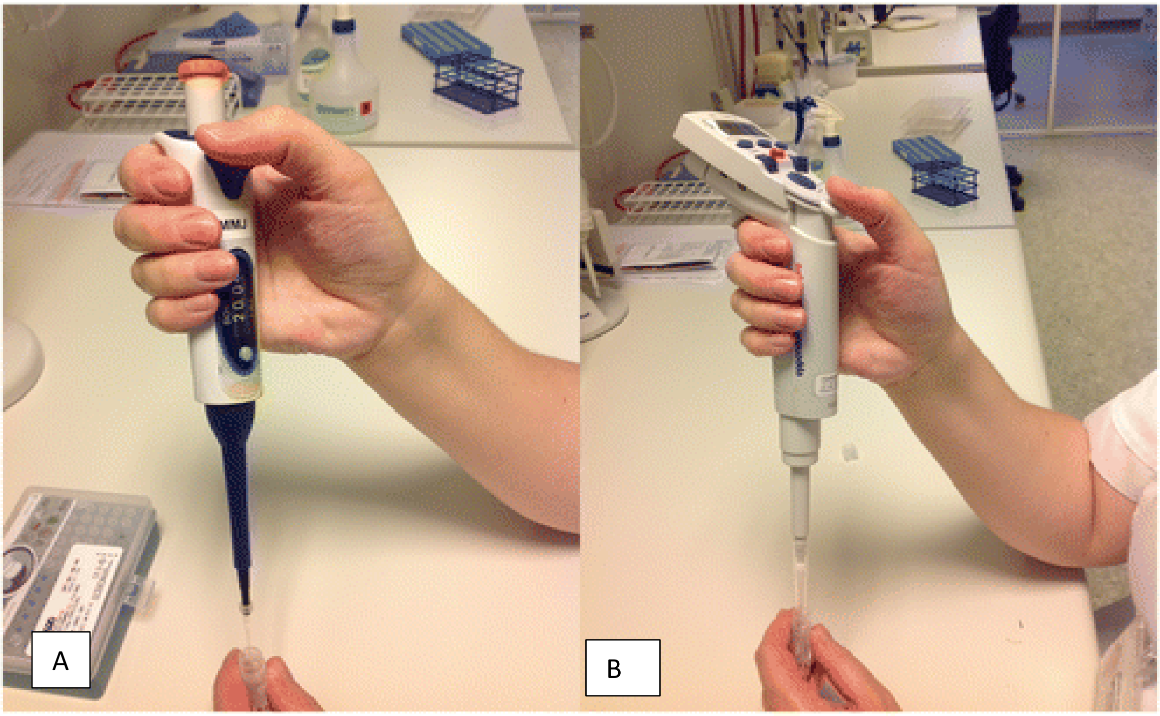

Figure 2: Types of pipettes. A represents manual thumb push pipettes and B represents automatic pipettes (Image taken from Holm et al., 2016).

Manual pipettes are commonly used in laboratories due to their flexibility (Holm et al., 2016; Wu et al., 2012). The use of these pipettes has been associated with a high prevalence of Musculoskeletal disorders among laboratory workers. Costello (2005) mentions that in 1995, the National Institute of Occupational Safety and Health (NIOSH) identified manual pipetting as the leading cause of MSDs in laboratories. Prolonged exposure to manual pipetting has resulted in MSDs and repetitive strain injuries (RSIs) of the upper limbs and neck (Costello, 2005; Kim et al., 2020).

Various studies have found a strong correlation between the prevalence of upper limb Musculoskeletal disorders and pipetting work (Björksten et al., 1994; David & Buckle, 1997; Holm, 2016). For instance, a study by Björksten and colleagues (1994) involving 128 laboratory workers revealed that 44% of the workers reported neck problems, 44% reported hand problems, and 58% reported shoulder problems associated with pipetting. Björksten and colleagues (1994) also found that a pipetting dose of more than 300 hours per year (8 hours per day) was associated with an increased risk of hand and shoulder ailments. David & Buckle (1997) also found that individuals who used pipettes for more than 60 minutes a day had increased elbow and hand complaints. In addition, Holm and colleagues (2016) reported that pipette work performed for more than two years was associated with an increased risk of MSD symptoms in the dominant upper limb, mainly in the shoulder, elbow, hand, wrist, and thumb. They also found that pipette work was associated with muscle pains in the neck-shoulder girdle and shoulder impingement syndrome in the dominant shoulder due to the repetitive and static nature of pipetting (Holm et al., 2016). Björksten et al. (1994) and David & Buckle (1997) reported that upper limb complaints were more frequent among pipette operators than non-pipette users.

2.3 Musculoskeletal disorders

It is crucial to understand the injuries and disorders associated with pipette use to understand the effects of manual pipetting on users.

Musculoskeletal disorders (MSDs) are a spectrum of inflammatory and degenerative injuries or disorders that affect the musculoskeletal system, including muscles, ligaments, tendons, spinal discs, nerves, joints, blood vessels, bones, etc., and result from exposure to various ergonomic risk factors (these risk factors will be discussed in the next section) (Mukhtad et al., 2018; Sirajudeen et al., 2018). These disorders usually develop over time, and symptoms range from mild to severe, often including pain, tenderness, stiffness, numbness, and discomfort (AlNekhilan et al., 2020). MSDs have a negative impact on the quality of life and impose a significant economic burden due to lost wages and compensation costs (Erick & Smith, 2011; Sirajudeen et al., 2018). Furthermore, Musculoskeletal disorders reduce productivity by increasing work absenteeism, sick leave, and early retirement (Mukhtad et al., 2018; Sirajudeen et al., 2018). In 2016, MSDs were reported to be the second most common cause of disability globally and have become a workplace epidemic, resulting in altered physical, psychosocial, and socioeconomic effects (Hoskins & Erickson, 1998; Roman-Liu et al., 2014; AlNekhilan et al., 2020).

2.3.1 Work-related musculoskeletal disorders

Work-related Musculoskeletal disorders (WRSMDs) occur due to continuous, vigorous, or prolonged exposure to work-related risk factors with insufficient recuperation (Erickson & Woodard, 2001; AlNekhilan et al., 2020). A strong association exists between physical risk factors such as repetitive movements, poor posture, high forces, static work or vibration, and the occurrence of work-related Musculoskeletal disorders (Mukhtad et al., 2018; van Tulder et al., 2007).

2.3.2 Upper limb Musculoskeletal Disorders

Manual pipetting is associated with various upper limb Musculoskeletal disorders (ULMSDs), which are disorders of the neck, shoulders, hands, arms, wrists, and fingers that are characterized by frequent pain accompanied by disability, varying in severity and impact (Akodu et al., 2015). Work-related upper limb musculoskeletal disorders are among the most significant and costly health issues impacting the working population, especially in industries that use hand tools (Aptel et al., 2002; Roquelaure et al., 2009). They result from exposure to various ergonomic risk factors such as repetition, awkward postures, and forceful actions.

Prolonged exposure to highly repetitive manual work has been associated with the development of ULMSDs and repetitive strain injuries (RSIs) (Lacerda et al., 2005; Wu et al., 2014). Repetitive strain injuries are any injuries that occur due to prolonged exposure to repetitive, forceful, or awkward movements and affect the upper limbs (especially the wrist, hand, neck, back, and shoulders) (Lacerda et al., 2005; Roman-Liu et al., 2014). Given that most tasks involve the use of upper limbs, these areas of the worker's body are often at a high risk of developing RSIs such as Carpal Tunnel Syndrome and Tendinitis (Roman-Liu et al., 2014). In addition to the hand, the thumb is essential in daily tasks such as grasping and pinching. Occupational tasks that require intensive and repetitive thumb motions have been linked to the development of thumb osteoarthritis (Jonsson, 2009; Wu et al., 2014). One such task is the use of thumb-operated mechanical pipettes, which require repetitive and forceful loading of the thumb and hand and put workers at risk of injury.

2.4 MSD risk factors

Musculoskeletal disorders are attributed to having a multifactorial aetiology, with work-related risk factors contributing significantly to the disease (AlNekhilan et al., 2020). Risk factors are any sources or situations that can result in injury or the development of a disease (AlNekhilan et al., 2020). van Tulder and colleagues (2007) explain that risk factors associated with RSIs, and MSDs can be classified into physical, psychosocial, and individual risk factors. A strong association exists between physical risk factors and MSD development. The main work-related physical risk factors associated with ULMSDs include high forces, sustained awkward postures of the wrist, elbows, or shoulders, vibrating hand tools, and repetitive motions (Mukhtad et al., 2018; Sirajudeen et al., 2018). Prolonged exposure to one or more of these risk factors increases the risk of MSD development. For instance, tasks involving highly forceful and repetitive actions are associated with a high prevalence of upper limb MSDs and work-related overload injuries such as Carpal Tunnel Syndrome (Silverstein et al., 1986; Higgs et al., 1992; Roman-Liu et al., 2014).

Manual pipetting involves various ergonomic stressors of the upper limbs (ARTEL, n.d.). These stressors (risk factors) include repetitive work, high forces, static loading, and awkward postures (Andersen, 2004; Unyi & Asato, 2015). Continuous exposure to these risk factors has been associated with the development of MSDs and injuries common among pipette users, such as Carpal Tunnel Syndrome and de Quervain's tenosynovitis, which may impact work productivity and longevity (Andersen, 2004; Holm, 2016; Rainin, 2016).

Given that repetitive manual pipetting exposes laboratory workers to several ergonomic risk factors, it places them in a high-risk category for developing Musculoskeletal disorders (Holm, 2016). Thus, to reduce the MSD risk associated with manual pipetting, pipetting tasks and pipette design should be designed in such a way as to reduce the high forces, repetitive motions, static activity, and awkward postures resulting from pipetting. This can only be achieved by understanding the mechanisms of pipetting (Selvaraj, 2014).

2.5 Mechanisms and Components of manual pipetting

According to Aptel and colleagues (2002), the design of hand tools should consider the user, the tool, the workplace/task, and the interaction between these components (refer to Figure 3, page 14). The user component comprises of individual characteristics such as anthropometry, health status, physical capabilities, skills, demographics, experience, personality, goals, motivations, etc., and the tool element comprises of the design elements of the tool such as tool weight, length, handle size, grip, grip diameter, balance of tool in hand, tool material, and functional characteristics of the tool. Workplace refers to factors relating to work tasks (i.e. job demands, cognitive demands and job content), work environment (aspects of the physical environment and work station design), and organizational factors (work shift and work structure) (Pheasant, 1996; Carayon & Smith, 2000; Aptel et al., 2002).

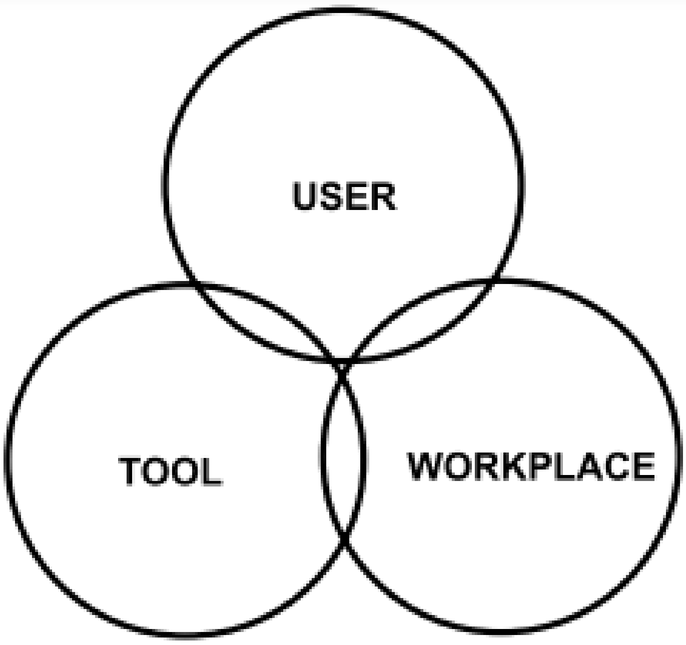

Figure 3: Components to consider in hand tool design. Image derived from Aptel et al. (2002).

The interaction between the abovementioned components produces various physical and psychosocial stressors and demands placed on the individual, resulting in a stress load/strain (Carayon & Smith, 2000). Physical stressors comprise ergonomic risk factors such as repetitiveness, high forces, and awkward postures. Psychosocial stressors consist of subjective experiences and perceptions of the work environment or task that can result in stress (Carayon & Smith, 2000). The strain placed on users impacts their biophysical (i.e., muscle activation, energy expenditure, health), performance, and psychological (perception, emotion) responses and is typically dependent on individual characteristics such as skill, motivation, physical capacity, health status etc., (Carayon & Smith, 2000). Prolonged exposure to work stressors, as well as an imbalance/mismatch between the physical and psychosocial demands of a tool or workspace and an individual's capabilities, can result in unfavourable outcomes such as reduced productivity, the onset of fatigue and the development of Musculoskeletal disorders (Pheasant & Haslegrave, 1996; Carayon & Smith, 2000).

In the context of manual pipetting, the use of manual pipettes exposes users to various ergonomic stressors of the wrist, arm, neck, and shoulders, including static muscular loading, repetition, awkward postures, and high forces (Unyi & Asato, 2015). In addition to the physical stressors associated with manual pipetting, occupational (psychosocial) factors and task demands such as time constraints, task accuracy, and productivity pressures, which are inherent in laboratory work, contribute to the stress load placed on pipette users (Penkala et al., 2018). Exposure to these stressors increases the risk of ULMSD development among pipette operators (Rainin, 2016). Due to the technique-dependency (dependent on accurate and precise work) of pipetting, reduced performance due to pain or discomfort resulting from MSDs may affect the user's accuracy and precision during pipetting tasks, factors which are integral in pipetting (Rainin, 2016).

The stressors placed on pipette users during manual pipetting stem from the interactions between pipette design (tool), task demands, and individual characteristics. The interactions and stressors (risk factors) linked to each component are shown in Figure 4, page 16 and explained below.

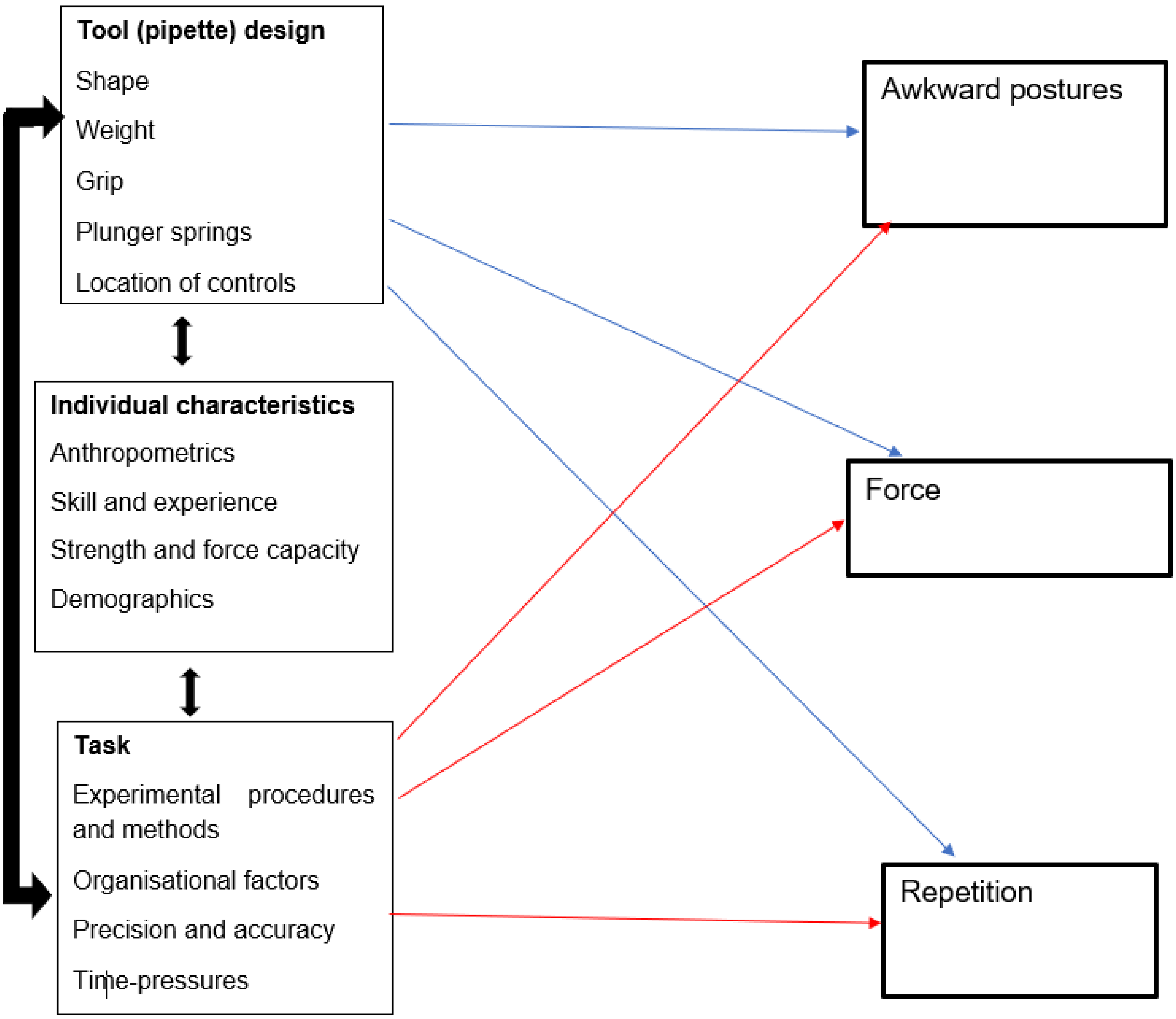

Figure 4: The interactions between pipette design, individual characteristics, and task demands. The red and blue lines depict the risk factors associated with each component. Risk factors include awkward postures, high forces, and repetition.

2.5.1 Individual

Individual factors such as age, anthropometrics, experience, skills, health status, strength, force capabilities, and gender are co-founding factors that contribute to the MSD risk placed on pipette users (Malchaire et al., 2001). Women have been reported to be at a higher risk of developing Musculoskeletal disorders than men due to physiological differences such as body size and muscular structures (Costello, 2005; Penkala et al., 2018; Roquelaure et al., 2009). In the case of manual pipetting, women are reported to be more susceptible to thumb strain during pipetting because of weaker muscular structures than males, and the force required to operate pipettes often exceeds their force capabilities (Fredriksson, 1995). The risk and degree of thumb strain and ULMSDs also increases with age and are dependent on the techniques used by pipette operators (Fredriksson, 1995; David & Buckle, 1997).

Björksten and colleagues (1994) found that psychological factors such as perceived work content (boring and mentally inactivating work) contribute to the prevalence of shoulder ailments among individuals that use pipettes. Several studies report that user comfort and usability also contribute to the MSD risk associated with manual pipetting (Lichty et al., 2011; Lintula & Nevala, 2006; Sormunen & Nevala, 2013).

Individual force capabilities

Individual force capabilities can infer the degree of muscular strain placed on users during pipetting. The maximum strength capacity for thumb-pinching and squeezing tasks ranges from 5 to 7 kg for women and 10 kg for men. In addition, dynamic activities requiring repetitive force exertion of more than 20%-30% of the user's maximum strength capacity (more than 2.1 kg and 3 kg for females and males, respectively) place users at risk of injuries and the development of MSDs (Burt, 2016; Rainin, 2016). The endurance limit for static force production is 15% of maximum capacity (1.1 kg and 1.5 kg for females and males, respectively) over 10 minutes of static contraction and decreases with an increased duration of force production (Bjorksten & Jonsson, 1977; Rainin, 2016). Forces exceeding these thresholds pose a risk for MSD development on users.

2.5.2 Tool design

The use of hand tools such as pipettes affects users' health, comfort, performance, and biophysical outputs, and has been linked to upper limb injuries (Aptel et al., 2002; Edgren et al., 2004; Lintula & Nevala, 2006; Sormunen & Nevala, 2013). A combination of intensive and repetitive work performed in awkward postures while using hand tools without good ergonomic design places additional strain on the musculoskeletal system and can lead to MSD development (Sormunen & Nevala, 2013; Rainin, 2016). As a result, the use of manual pipettes has been associated with a high prevalence of upper limb MSDs, such as tendonitis (Sormunen & Nevala, 2013; Rainin, 2016). Various studies report that the design of pipettes and how they are used are major contributing factors to the MSD risk associated with manual pipetting (Hoskins & Erickson, 1998; Lee & Jiang, 1999; Asundi et al., 2005).

According to Edgren and colleagues (2004), the design of hand tools and workspaces influences muscular loading and postures, and features such as tool size and shape contribute to the occurrence of various MSDs, such as Carpal Tunnel Syndrome, as they increase carpal tunnel pressure. As such, the design of axial manual pipettes has been found to influence forces applied, posture, hand and thumb muscular activity, perceived comfort and usability, and performance (Asundi et al., 2005; Kim et al., 2020; Lee & Jiang, 1999; Lichty et al., 2011; Lintula & Nevala, 2006; Lu et al., 2008; Rempel et al., 2008; Sormunen & Nevala, 2013; Wu et al., 2014). Technical characteristics of the pipette, such as weight, length, shape, grip, circumference, finger rest, plunger forces, and location of controls, contribute to the strain placed on the upper extremities and increase the risk of ULMSD development (Lichty et al., 2011; Sormunen & Nevala, 2013).

High forces

Manual pipetting requires high levels of hand and thumb muscle forces for tip insertion, tip ejection, plunger manipulations, and blowout forces (Erickson & Woodard, 2001; Asundi et al., 2005; Lu et al., 2008). The magnitude of the forces generated is determined by the resistance of the pipette plunger, viscosity of the liquid to be pipetted, the force required to lift and stabilize the pipette, the precision of the pipetting task as well as the force required to ensure aspiration and the dispensation of liquids (Lu et al., 2008; Integra, n.d.). In addition, Andersen (2004) highlights that the forces required to operate the plungers and buttons vary among different pipette models, whether they are manual or automated, and whether they have been ergonomically designed.

A complete pipette cycle during manual pipetting consists of tip insertion, fluid aspiration, fluid dispensation, and tip ejection (see Figure 1, page 8) (Lichty et al., 2011; Rainin, 2016*).* The forces required to perform these actions have been reported to exceed recommended maximum strength capacity levels and pose a risk for injury and MSD development (Fredriksson, 1995; Erickson & Woodard, 2001; Rainin, 2016).

Plunger forces required for fluid aspiration and dispensation amount to 4 kg and exceed the recommended peak force levels of 3 kg and 2.1 kg for males and females

(Rempel et al., 2008). The high plunger forces are attributed to the resistance of the two springs in the plunger, which allow for aspiration and dispensation. The springs are of different resistance, as they provide accuracy and precision by allowing the user to locate and hold the first stop (Rainin, 2016). The first spring is light and requires low forces of 1 kg for aspiration and dispensation. In contrast, the second (blowout) spring is heavier and requires high forces (4.4 kg) as it is designed to resist the pressure exerted by the user to allow the user to find and lock the first stop between the aspiration and blowout positions (Fredriksson, 1995; Rainin, 2016). Asundi and colleagues (2005) found that blowout forces vary between 23 N to 35 N as users decide where to stop when depressing the plunger.

In a study assessing the thumb push forces required to operate a pipette as a percentage of maximum thumb strength, it was found that pipette operating peak push forces were 14,5 % and 18,4 % of maximum push force capacity for male and female individuals, respectively (Fredriksson, 1995). The study also revealed that the force required to press the pipette button down to the different stops was 5.4 % (4.2 N) and 18.4 % (14.2 N), which exceed recommended peak push levels (Fredriksson ,1995).

Tip insertion forces are reported to exceed 5.5 kg and vary depending on mounting techniques used by operators (i.e., operators press pipette into tip/ press and rotate/pounding/ finger tightening, etc.) (Erickson & Woodard, 2001; Rainin, 2016).

Tip ejection forces range from 1 kg to 8 kg (average 4 kg), and with traditional pipette models increased tip insertion forces result in higher tip ejection forces (Rainin, 2016). This is due to the lack of a feedback mechanism when the tip is sealed (as users tend to overexert the force required to seal the tip onto the shaft) as well as the large sealing area that exists between the shaft of the pipette and the tip which result in increased frictional forces when the tip is inserted (Rainin, 2016). This, in turn, results in high forces required to eject the tip. Thus, it was reported that tip ejection makes up 40% of the force exerted during a pipetting cycle (Rainin,2016).

Asundi et al. (2005) also mention that volume adjustment, which includes the manipulation of the rotating dial using the thumb or finger, results in increased thumb muscular loading. This is because of the small diameter of the dial, restricted contact between the dial and fingers, and the force required to turn the dial.

Grip, grip circumference, weight, and length of pipettes

According to Erickson & Smith (2007) and Burt (2016), grip type and grip size (grip diameter) influence muscle forces generated during pipetting. Pipettes involve a combination of a power grip and a precision grip (Fredriksson, 1995). A power grip involves intrinsic and extrinsic muscles of the hand as the wrist is stabilised, and all the fingers are involved in the firm gripping of the tool (Finneran & O'Sullivan, 2013). In a precision grip, the intrinsic muscles of the hand perform fine movements of the fingers while the hand and wrist are stabilised by flexor and extensor muscles (Finneran & O'Sullivan (2013). During manual pipetting, the pipette is held perpendicular to the proximal axis of the forearm, with the palm facing the user (refer to Figure *2*, page 10). While holding the pipette, the four fingers grasp the pipette, and the muscular structures must produce a counterforce. A precision grip is then used to press the plunger down with varying force (Fredriksson, 1995; Lee & Jiang, 1999). Hand grip during manual pipetting often varies depending on the type of pipette used and influences wrist postures and the muscular loading of the hand and thumb (Lu et al., 2008). Finneran & O'Sullivan (2013) point out that a combination of incompatible grip type and force affects the kinematics of the upper limb and lead to increased muscle fatigue.

According to Radwin (2003), grip strength is affected by the hand joints and muscles' position and length relative to the tool. Thus, increased grip diameter (greater than 5cm) results in reduced grip strength as the contact between the hand and tool is affected by the hand size relative to the tool's size (Lee & Jiang, 1999; Edgren et al., 2004). In manual axial pipetting, the diameter and shape of the pipette require a tight grip, which results in high hand grip forces and reduced hand strength (Lu et al., 2008).

The weight and length of the pipette have also been found to affect the muscular strain in the shoulder, arm, and wrist caused by holding the pipette in static positions (Hoskins & Erickson, 1998; Lu et al., 2008).

Awkward postures

According to Hambali and colleagues (2019), awkward postures are any unusual (non-neutral) positions that the body assumes. These positions cause strain to the musculoskeletal structure of the body resulting in pain, fatigue, injury, and restricted motion. Awkward postures are typically related to the design of workstations and tools (Hambali et al., 2019). In the context of manual pipetting, the design and use of axial pipettes result in awkward postures of the hands, arms, elbows, shoulders, neck, and wrists (Fredriksson, 1995; David & Buckle, 1997; Lee & Jiang, 1999; Costello, 2005; Lu et al., 2008).

Shoulders and arms: The overall length and axial shape of traditional mechanical pipettes cause users to engage in awkward postures, and contribute to the static loading of the shoulder, arm, and neck (Costello, 2005; Lu et al., 2008; Lichty et al., 2011). During pipette operation, users often abduct and elevate their pipetting shoulder and arm between 45 and 90 degrees in front of the body to obtain a good work surface clearance (Costello, 2005). The insertion of a disposable tip to the pipette shaft further increases the height at which pipette operators perform pipetting tasks (approximately 20-25 cm above the workbench), resulting in users maintaining static arm abduction (David & Buckle, 1997; Costello, 2005; and Lu et al., 2008). Costello (2005) explains that the static muscle loading is a result of the arm inertia as the arm is suspended over the work surface throughout a pipetting task. Prolonged arm and shoulder abduction during pipetting increases the risk for ULMSDs of the neck, shoulder, and arms (Costello, 2005; Lichty et al., 2011).

Thumb: During pipetting using a traditional axial pipette, the thumb works as a stabilizer and mobilizer to stabilize the grip around the pipette to push the pipette plunger, and enable the fine, well-controlled movements of the pipette tip. This increases the strain on the thumb muscles, as the muscles work twice as hard (Fredriksson, 1995; Lintula & Nevala, 2006; Holm et al., 2016). When depressing the plunger, the thumb is flexed, inwardly rotated, and extended, resulting in an unstable joint position that increases the tension and loading of the thumb (VistaLab Technologies, 2001; Holm et al., 2016). The extent to which the thumb is extended depends on the height of the plunger, and given that most mechanical pipettes have a separate plunger and ejection button, the thumb must extend further to reach the ejection button (Lee & Jiang, 1999; Erickson & Woodard, 2001). Continuous thumb loading and extension increase the strain placed on the thumb and the risk of repetitive strain injuries such as de Quervain's tenosynovitis (Hoskins & Erickson, 1998; Wu et al., 2014).

Wu and colleagues (2014) investigated the muscle-tendon loading of the thumb during pipetting using an inverse dynamic approach and a force sensor to measure forces exerted on the plunger. They measured the muscle force of nine thumb muscles, including Abductor Pollicis Brevis (APB), Abductor Pollicis Longus (APL), Opponens Pollicis (OPP), Extensor Pollicis Longus (EPL), transverse head of adductor pollicis (ADpt), Oblique head of adductor pollicis (ADpo), Flexor Pollicis longus (FPL), Extensor pollicis brevis (EPB) and Flexor Pollicis Brevis (FPB) muscles. They found that the FPB and APB (thumb flexor and abductor) muscles produced the most force (60 N and 68 N, respectively) because the thumb functions to grip and press the pipette during pipetting (Wu et al., 2014).

Wrist and Forearm: According to Keir and colleagues (2007), awkward wrist postures pose a risk for hand and wrist injuries such as tendon related disorders and Carpal tunnel syndrome (CTS). CTS occurs when the median nerve, which runs along the index finger and thumb flexor muscles, is exposed to mechanical compression or friction in the carpal tunnel (Barr & Barbe, 2002; You et al., 2014). Awkward positions such as extreme wrist flexion or extension and non-neutral forearm pronation-supination contribute to increased carpal tunnel pressure (Barr & Barbe, 2002).

Manual pipetting requires frequent pronation and supination of the forearm during the transfer of fluid from one container to another (Burt, 2016). This places high pressure on the median nerve which can get impinged or inflamed and result in injuries such as Tennis elbow (Integra, n.d.). In addition, pipetting actions such as tip insertion, aspiration, dispensation, and tip ejection, involve frequent and excessive wrist extension and ulnar deviation, which exceed recommended wrist joint thresholds reported by Keier et al. (2007) and Ketola et al. (2010) (Lu et al., 2008; VistaLab Technologies, 2011; Sormunen & Nevala, 2013; Burt, 2016; Kim et al., 2020). This places pipette users at risk of developing RSIs such as CTS.

Pipetting in non-neutral wrist postures increases the risk of hand muscle fatigue due to a reduction in maximal isometric hand forces that can be exerted in those positions (Lu et al., 2008; Burt et al., 2016).

Several studies also report that pipette weight, length, and circumference influence wrist positioning and the muscular loading of wrist muscles (Lintula & Nevala, 2006; Sormunen & Nevala, 2013).

While analysing pipetting posture using a video recording analysis, Fredriksson (1995) found that a typical pipetting posture results in neck flexion (30°), 20° shoulder abduction, elbow flexion (90°), 30° arm supination, and 30° wrist extension. These awkward postures may lead to muscular strain and increase the risk of ULMSDs (Fredriksson, 1995). Increased exposure to awkward wrist, forearm, elbow, neck, and shoulder postures/positions increases the risk of MSD development and the pains associated with these disorders can reduce precision, accuracy, and productivity (Burt, 2016).

2.5.3 Task demands

Repetition

According to Asundi et al. (2005), manual pipetting involves highly monotonous and repetitive motions during the performance of the pipetting cycle. The pipette cycle includes tip insertion, fluid aspiration, fluid dispensation, and tip ejection. These actions are shown in Figure 1, page 8 and described by Asundi et al. (2005) and Kim et al. (2020) as follows:

1.Tip insertion - The user exerts effort to mount the disposable pipette tip firmly on the shaft by rocking, jamming, pounding, or pushing the tip onto the shaft.

2. Fluid aspiration – The pipette operator uses their thumb to depress the plunger to the first tactile stop position (stop depends on the volume set on the pipette). The user then holds the plunger in this depressed position with their thumb while they hold the pipette vertically and place the pipette tip into the sample fluid to be aspirated. The plunger is then slowly released in a controlled manner to suck up fluid into the tip. Once the tip is filled with fluid, the user then locates the target container to dispense fluid.

3. Fluid dispensation- Once the target container is located, the user then depresses the plunger to the first stop to release fluid from the pipette tip into the target container. The residual fluid left in the pipette tip is dispensed through a “blowout force” whereby

excess force beyond the first stop is applied onto the plunger. The plunger is then released and returned to its original position.

4.Tip ejection – The user then ejects the disposable tip from the pipette shaft by pressing another thumb-operated button (the ejection button) located on the pipette.

These actions are continuously repeated several times within a work shift depending on the experimental procedures used (Integra, n.d.). The highly repetitive and forceful nature of pipetting increases the risk of laboratory workers developing ULMSDs. McGlothin & Hales (1996) report that workers in drug production labs complete between 6000 to 11700 repetitive motions per day while using pipettes. They also found that pipetting in these labs exceeded 500 hours per year and approximately 1 500 000 to 2 925 000 repetitions per year McGlothin & Hales (1996).

Force

Several studies report that pipetting tasks, especially precision tasks, increase the static loading of thumb and shoulder girdle muscles, and increase the risk of muscular fatigue (Asundi et al., 2005; Lu et al., 2008; Holm et al., 2016). Asundi et al. (2005) and Lu et al. (2008) investigated thumb forces and muscle activity during manual pipetting and found that increased pipette precision resulted in increased static muscle activity of thumb muscles, and reduced peak thumb force (Asundi et al., 2005; and Lu et al., 2008). This is because increased pipetting task precision requires more thumb control which results in increased static loading of thumb muscles and may contribute to increased risk of tendon-related injuries or fatigue i.e., tendinitis (Asundi et al., 2005; Lu et al., 2008). Furthermore, precision tasks have been found to result in increased forearm muscle loading and perceived difficulty which may lead to discomfort and reduced productivity (Finneran & O'Sullivan, 2013).

Increased fluid viscosity has also been reported to increase peak thumb forces, cycle time and exposure to risk (Asundi et al., 2005).

Awkward postures

The nature of the task and the design of the workstation influence neck posture, as users often flex and rotate their necks for prolonged periods while performing pipetting tasks (David & Buckle, 1997). The precision with which pipette work is performed necessitates the abduction of the shoulder, resulting in increased static strain placed on the shoulder (Holm et al., 2016). Furthermore, pipetting work also involves the performance of pipetting tasks under narrow working conditions such as fume hoods, and biosafety cabinets which cause the pipetting shoulder to be abducted or flexed and the neck to be flexed for prolonged periods, increasing the muscular loading of the neck and shoulder (Lichty et al., 2011; and Holm et al., 2016).

In addition, the amount of pipette work done, the speed of pipetting, and the time spent pipetting results in sustained awkward postures and has been associated with several upper limb complaints (David & Buckle, 1997; Holm et al., 2016). This is because, during pipetting, the pipette operating upper limb is repeatedly moved between different sample containers/vessels while maintaining static and awkward postures (Holm, 2016).

Psychosocial work dimensions such as low job demands and low job control were found to be determinants for upper limb symptoms (Holm et al., 2016). AlNekhilan and (2020) colleagues investigated the prevalence of work-related musculoskeletal disorders in the clinical laboratories of six government hospitals in Saudi Arabia. They found that age, duration of work, laboratory division, and the nature of the job were all risk factors for developing WMSDs. The nature of the job was associated with the affected parts of the body; workers performing manual tasks such as pipetting were found to be more susceptible to experiencing neck and shoulder pain (AlNekhilan et al., 2020).

2.6 Integration of ergonomics to pipette design

The interaction between the abovementioned pipetting components/risk factors results in a task that places pipette users at a high risk of developing various Upper limb Musculoskeletal disorders. To reduce the MSD risk associated with manual pipetting, manual pipettes should be redesigned and factors such as user preference, familiarity, individual characteristics of pipettors (i.e. hand size, grip strength), technical requirements, the weight of pipette, location of pipette controls, use of multiple finger controls, force required to operate controls, task requirements, pipetting duration and speed, and body positions needed to operate the pipette, should be taken into consideration when designing pipettes and pipetting tasks (Hoskins & Erickson, 1998; Lee & Jiang, 1999; Lu et al., 2008; Erickson & Smith, 2007). In addition, improved pipetting practices should be developed, and ergonomic principles should be applied to pipette design (Rainin, 2016).

Ergonomics aims to improve performance, user well-being, and safety, and the integration of ergonomic principles into tool design comprises a user-centred approach (Pheasant, 1996; Carayon & Smith, 2000). A user-centred approach is one in which the design and characteristics of a tool or system are matched to the users' capabilities to achieve the best possible match between these components (Pheasant & Haslegrave, 2018). Thus, the integration of ergonomics to tool design aims to achieve an optimal balance between the interactions of the components shown in Figure 3, page 14. Ergonomic modifications to tasks or tools are common and effective strategies for reducing task physical demands the risk for upper limb MSDs (Baker & Jacobs, 2010). Aptel and colleagues (2002) explain that an ergonomically designed tool is one which is safe, efficient, and places reduced demands on the upper limbs to reduce the risk of WRMSDs.

Several studies have investigated the effects of pipette design on biomechanical, performance, and subjective responses (Lee & Jiang, 1999; VistaLab Technologies, 2001; Erickson & Smith, 2007; Lu et al., 2008; Lichty et al., 2011; Sormunen & Nevala, 2013; Lintula & Nevala, 2; Kim et al., 2020). They found that pipette design influences performance, posture, user comfort and usability, and hand and thumb muscular loading. A redesign and ergonomic modification to manual pipettes was found to be associated with various benefits such as improved performance, improved comfort and usability, reduced muscular strain, and reduced awkward postures, due to reduced plunger forces, a change in pipette grip, and a change in plunger operation mechanisms (Lee & Jiang, 1999; VistaLab Technologies, 2001; Lu et al., 2008; Kim et al., 2020). Kim et al. (2020) reported that redesigning a thumb-push pipette to a four-finger operated push pipette had a better ergonomic design compared to the traditional thumb-push pipette, and reduced muscle exertion, awkward wrist postures, and discomfort in the hand, wrist, and forearm. Lu and colleagues (2008) also found that non-axial pipettes reduced hand forces, and wrist and shoulder postural stressors which pipette users are exposed to during pipetting.

The abovementioned studies report that an ergonomically designed pipette is one which would reduce tip insertion, ejection, and plunger forces, and include a comfortable handle. Critical factors in pipette design should include low plunger forces, high accuracy and precision, comfortable grip, reduced pipette weight, easy tip insertion and ejection, ease of volume adjustment, good fit, and a well-balanced feel (Lee & Jiang, 1999; Erickson & Smith, 2007; Lichty et al., 2011; Rainin, 2016). Lintula & Nevala (2006) and Sormunen & Nevala (2013) also report that pipettes should be short and light to reduce muscular strain and awkward wrist postures. In addition, these pipettes should be designed to reduce repetition and ensure neutral postures (Rempel et al., 2008). In conjunction with functional characteristics, the interaction between the pipette and individual's capabilities (i.e., skills, anthropometry, etc) should be considered (Lee & Jiang,1999). The combination of functional and human requirements is an important ergonomic aspect to consider when designing pipettes (Lee & Jiang, 1999).

2.7 Assessment methods to study pipetting

Given the high prevalence of ULMSDs associated with manual pipetting, quantifying, and assessing the risk placed on users is critical to the redesign of manual pipettes. MSDs are multifactorial in nature and are associated with physical, psychosocial, organisational, and individual risk factors (David, 2005; Malchaire et al., 2001). Various methods have been developed to assess and prevent the exposure to MSD risk factors. These methods include self-reports, observational methods, and direct measures (David, 2005), and can be used to assess the risk factors affecting the upper limbs during pipetting.

Since manual pipetting influences muscular loading, wrist postures, performance, user comfort and usability, these factors were measured and assessed using the methods described by David (2005). Electromyography, goniometry, and subjective measures were used to assess the risk factors associated with manual pipetting.

2.7.1 Electromyography

Electromyography (EMG) is a direct method used to observe muscle function through the measurement and detection of electrical signals generated during muscle contractions (Rash, 1999; Kuriki et al., 2012). These signals are detected through the placement of electrodes on the skin surface or insertion into the muscle tissue, and the detected signals generate a waveform on the EMG computer known as an electromyogram which represents neuromuscular activity (García & Vieira, 2011). During muscle contraction, depolarization of the motor units generates an electromagnetic field, and the potential is the measured signal. The signal represents a collection of motor unit action potentials (MUAP) that are responsible for muscle contraction (Rash, 1999; García & Vieira, 2011). The extent to which MUAPs are detected depends on the number of motor units active during contraction and the type of electrodes used (García & Vieira, 2011).

Electromyography is often used to analyse performance associated with the workplace (Marras, 2016). In Ergonomics, EMG can be used to measure musculoskeletal stresses in various muscles, associated with work stresses such as posture, intensity, duration, etc (Marras, 2016).

EMG signals can be measured using intramuscular or surface electrodes (Merletti et al., 2001). Intramuscular EMG is an invasive method that involves the insertion of a needle electrode into a muscle tissue of interest (Rash,1999). Surface EMG (SEMG) is non-invasive and involves the placement of electrodes on the skin surface of the muscles of interest (Chowdhury et al., 2013). SEMG detects electrical activity of motor units located at the region where electrodes are placed. The EMG signal is then detected by the electrodes and amplified to indicate an EMG amplitude (Kuriki et al., 2012; Reaz et al., 2006). The quality of the detected signal is altered by a combination of noise signals and artifacts such as the presence of electronic equipment, physiological factors, or artifacts that stem from the attributes of the EMG signal (Chowdhury et al., 2013). These attributes are dependent on the internal structure of an individual, i.e., skin formation, blood flow velocity, skin temperature, and tissue structure of the measurement site and can be minimized through the placement of a first-stage amplifier close to the electrode site (Chowdhury et al., 2013; Robertson et al., 2014).

Surface Electromyography

Surface Electromyography (SEMG) provides a safe, easy, and non-invasive method for objective measurements of muscle activity (Cram & Kasman, 2011). SEMG is also advantageous in movement applications as it allows for the observation of changes in muscle activity in different muscles, from rest throughout the movement (Rash, 1999; Cram & Kasman, 2011).

SEMG is limited in that crosstalk occurs whereby the signals recorded are difficult to discriminate between underlying muscles and adjacent muscles because the surface electrodes have a large pick-up area and therefore have more potential to pick up muscle activity from muscles adjacent to the muscle of interest (Rash, 1999;

Robertson et al., 2014). Surface electrodes are also limited to only detecting surface muscles ranging from 10 to 20 mm from the skin to the surface and thus, can only accurately record and infer superficial muscle activity as opposed to deeper muscles or deeper portions of large muscles (Rash, 1999; Robertson et al., 2014). Another limitation is that the depth of subcutaneous tissue at the measurement site influences recorded signals, which is dependent on inter-subject variability such as body weight (EMG signals are more accurate with individuals with lower body fat and more compliant skin). Lastly, there are only a few published guides for electrode placements, of which none have been standardized (Cram & Kasman, 2011).

Information gathered using Electromyography

Electromyography provides information on the relationship between temporal aspects of the signal and anatomically associated movements, muscle force production, and muscle fatigue (Gerleman & Cook, 1992). Temporal information refers to the activity or inactivity of a muscle during movement or at any given point in time (Gerleman & Cook, 1992).

Several authors (Gerleman & Cook,1992; Kuriki et al., 2012) highlight that it is not possible to directly measure muscle force using EMG, and that this can only be achieved through the relativization of the measured signal for a particular muscle during a given activity using a percentage of maximum voluntary contraction of that muscle. “EMG force measurements quantify the average number and firing rate of motor units contributing to a given muscle contraction and relate to the force produced” (Gerleman & Cook,1992, Chapter 4, p. 44-45). This means that when the intensity of a contraction increases, more motor units are activated and the unit firing rate increases resulting in a dense interference pattern and a greater amplitude (Gerleman & Cook, 1992). Thus, the amplitude of the electromyogram of a given muscle indicates the degree of muscle activation and muscle force (García & Vieira, 2011). Muscle force measured depends on various factors such as types of muscle fibres recruited, contraction type, muscle mechanical work, length of muscle fibres, etc., (García & Vieira, 2011). In addition, the type of electrodes used influence the detected signal and muscle force observed (Gracia & Vieira, 2011). Rash (1999) and Kuriki et al. (2012) argue that the validity of the relationship between EMG and force production is questionable for various reasons such as cross talk, variations in electrode placement, and the involvement of synergistic muscles in force generation.

Electromyography can also provide information on localized muscle fatigue (Gerleman & Cook, 1992). However, for the purpose of this study, muscle activity was recorded to infer on muscle force during pipetting.

2.7.2 Electrogoniometry

Manual pipetting results in awkward joint postures, especially of the wrist, forearm, shoulder, and neck (Lu et al., 2008; VistaLab Technologies, 2011; Burt, 2016). Awkward wrist postures have been attributed to increased intercarpal pressure and the development of Repetitive strain injuries such as CTS (Keir et al., 2007). Thus, in this present study, wrist posture and range of motion was measured using electro-goniometry to determine the strain placed on the wrist during manual pipetting.

The electro-goniometer (EGM) is a useful tool in the functional evaluation of different joints and their range of motion (Foltran et al., 2013). Electro-goniometers can be used for the assessment of wrist postures and angles assumed during typical work tasks (Hughes & Babski-Reeves, 2016). Joint angle and movement measurements can be used to characterize posture, repetitiveness, and joint movement velocity (Jonsson, 2009).

Electro-goniometers are advantageous because of their lightweight design which allows individuals to perform tasks with minimal interference, they are portable, easy to operate, relatively inexpensive, easy to use for data collection and analysis, and can be applied to various occupational settings (Foltran et al., 2013; Hughes & Babski-Reeves, 2016). In addition, EGM recordings are not influenced by other electrical devices, large quantities of data can be recorded, and EGMs can record for long durations (Foltran et al., 2013).

These devices, however, have limited accuracy due to crosstalk, whereby movements performed primarily in one plane of motion result in the inaccurate recording of movements in other planes of motion, and zero drift which occurs when non-zero (deviation) measurements are recorded in the plane of motion of interest (Foltran et al., 2013; Hughes & Babski-Reeves, 2016). Hughes & Babski-Reeves (2016), explain that crosstalk and zero drift are often a result of the twisting of the electrogoniometer sensing wires between the proximal and distal end-blocks during joint movements. Inherent errors are another limitation of the EGM whereby, identical sensors of the EGM device produce different measurement results. This is due to the way the sensing elements of the device are housed inside the sensor unit and generally occur with increasing Range of Motion as well as increased use of the sensor (Foltran et al., 2013).

2.7.3 Self report measures

As mentioned, MSDs are multifactorial in nature and thus, do not only have biophysical factors (David, 2005). For this reason, perceptual/ self-report measures are also recorded to gain a holistic view of the development of MSDs. Self-report measures provide information on subjective perceptions of workplace exposure to physical and psychosocial factors using methods such as questionnaires, interviews, diaries, etc. (David, 2005).

Self-report measures on the perception of tasks are good indicators of the relationship between tasks and workstation attributes, and enable the identification of tasks, equipment, or workstations with high risks (Krawczyk, 2012). Thus, self-report measures indicate the perceptual aspects between task demands and an individual's capabilities. Advantages of using self-reports is that they are easy to administer, applicable to a variety of work contexts, low cost and can be administered to a large sample (David, 2005). The disadvantages of this assessment method are that subjective measures can be biased, and unreliable, and varying levels of worker literacy and comprehension of questions can limit results obtained (David, 2005).

Borg Rating of perceived exertion (RPE) scale

In this study, the Borg Rating of Perceived Exertion (RPE) scale was used to obtain individuals' perceived exertions during manual pipetting using different pipette models. The Borg Rating of Perceived Exertion scale (Appendix A) is used to subjectively quantify an individual's effort and exertion, breathlessness, and fatigue during any physical task (Williams, 2017). The scale measures how hard the body is working based on the physical sensations experienced by an individual and integrates cues from peripheral muscles and joints, cardiovascular and respiratory functions as well as the central nervous system (Borg, 1990). The RPE scale is a psychophysical (quantification of sensation induced by a physical stimulus), category scale which ranges from 6 to 20, where 6 represents no exertion, and 20 represents maximal exertion (Ritchie, 2012). Individuals assign a value to a stimulus based on its proportion to a fixed standard on a perceptual scale. Individuals were required to report on local perceptions, which are perceptions of muscular effort.

5-point Likert scale

In addition to the RPE scale, a 5-point Likert rating scale, was used in the analysis of the subjective perceptions of comfort and usability of the different pipette models. A Likert scale is a psychometric response scale which measures the attitudes, experiences, values, or perceptions of individuals towards a given stimuli or situation (Joshi et al., 2015). Likert scales are typically three- or nine-point ordinal scales which require users to rank or rate the experienced intensity or level of agreement with a given statement relating to a particular item or situation (Joshi et al., 2015; Trimmel & Trimmel, 2017). The scale provides a range of responses to a given statement or question (i.e in a five point scale responses range from 5= strongly agree to 1=strongly disagree) and users are required to respond to the statement by selecting a verbal description anchored at a point value on the scale, as to rate the degree at which they perceive or agree with that statement (Croasmun & Ostrom, 2011; Trimmel & Trimmel, 2017). Likert scales are useful because they enable users who have difficulties in quantifying their subjective experiences in numbers to have the option of selecting verbal pre-defined values (Trimmel & Trimmel, 2017).

The measurement of subjective ratings on comfort and usability help mitigate the negative effects of tool design on users and provide further information on the usability and efficiency of the tool (Trimmel & Trimmel, 2017). Features such as length, balance, fit, force application, and ease of use contribute to the comfort of a tool and affect muscle activity, wrist positioning, and contribute to the MSD risk associated with tool use (Erickson & Smith, 2007). Thus, in this study a 5-point Likert scale was used to assess the comfort of these features in the different pipette models (refer to Appendix B).

2.8 Market Analysis

There are various pipette types and models produced by different manufacturers. These pipettes have varying features related to technical requirements, accuracy, efficiency, and vary in tool dimensions such as weight, length, grip, shape, operational forces, plunger and tip ejection systems, and other technical features.

A market analysis of traditional and ergonomically designed mechanical pipette models was conducted, a detailed summary of the characteristics of the pipette models is shown in Appendix C. In this study, two different pipette models were assessed: a traditional axial-shaped mechanical pipette model (see Figure 5, page 35) and a non-axial ergonomic model (see Figure 6, page 36). The two pipette models analysed are representative of the two groups of pipettes (Traditional and ergonomic models).

Chapter 3

Methodology

3.1 Research concept

Given that pipette design and features of the pipette affect muscular loading, postures, and user comfort, and contribute to the MSD risk placed on pipette users, a laboratory-based experimental study was conducted to assess the effects of pipette design on biomechanical, performance, usability, and comfort responses. The aim of the study was to compare two different manual pipette models by assessing the muscle activation, wrist positioning, task completion time, and perceptual responses during their use and to determine which pipette model can reduce the ergonomic risk associated with repetitive manual pipetting.

3.2 Research Design

To assess the ergonomic risk associated with pipette design, a one-factorial repeated measures design was used. Two pipette models were used to complete pipetting tasks while biomechanical, performance, and subjective responses were measured for each pipette model.

3.3 Independent Variables

<u>3.3.1 Pipette models</u>

The study included the use of two different pipettes - a traditional axial pipette and an ergonomically modified non-axial pipette model. The pipette models used in this study included the Lasec^{TM} Adjustable Volume (AV) pipette and the VistaLab^{TM} Technologies Ovation^{R} pipette. The Lasec^{TM} AV pipette model was selected due to its common use in laboratories, and its accessibility and availability in the Rhodes University science laboratories. The VistaLab^{TM} Technologies Ovation^{R} pipette was used in this study due to its ergonomic design and mentions in literature recommendations (VistaLab Technologies, 2001; Costello, 2005).

The Lasec^{TM} AV pipette (Figure 5, page 35) is a traditional, and mechanical pipette model. The Lasec^{TM} AV pipette is elongated/axial shaped, thumb-operated, and uses an air-displacement mechanism to allow for fluid aspiration into the disposable tip (Lasec, 2015). The Lasec^{TM} AV pipette consists of a separate plunger operation button, a separate adjustable ejection button, a vertical shaft situated at the bottom of the pipette for tip insertion, a rotating volume adjustment knob, a volume display window situated on the body of the pipette, and a fixed finger hook for comfort and ease of pipette operation (Lasec, 2015). The pipette plunger operates as a pushbutton for aspiration and dispensation, and as a volume adjustment knob. Newer models of this pipette have been modified to reduce thumb push forces during pipetting, and the ejection button has also been modified to be adjustable and reduce forces during tip ejection (Lasec, 2015). Disposable tips are inserted at the end of the pipette shaft by twisting or jamming them onto the shaft to ensure an airtight seal, and they are ejected using the ejection button. The volume range of the pipette is displayed on the pipette body, and for the purpose of this study the volume range used was 100 microlitres to 1000 microlitres.

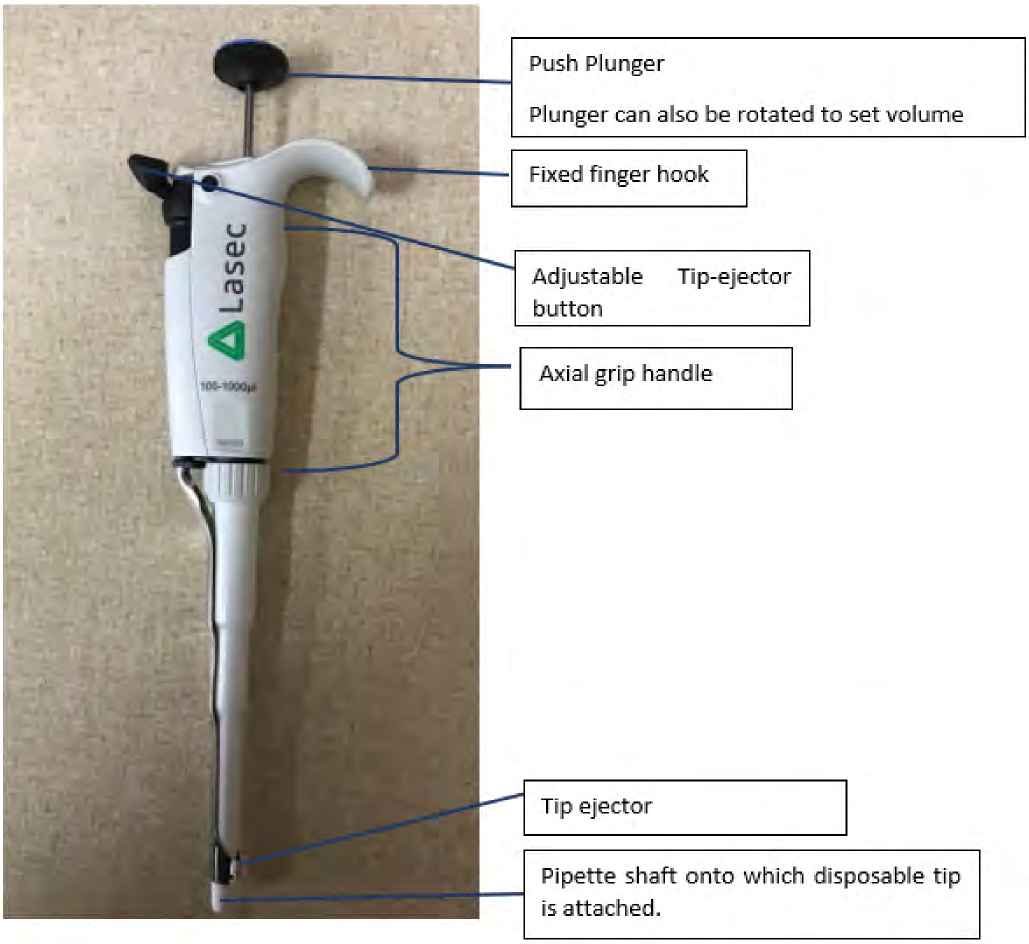

Figure 5: A Traditional mechanical pipette model - Lasec^{TM} Adjustable volume pipette

The VistaLab^{TM} Technologies Ovation^{R} pipette (or Vista in short) (see Figure 6, page 36) is a more complex and ergonomically modified pipette model. This pipette model has a non-axial design and a large grip circumference as the body of the pipette is designed in such a way that it fills the palm of the user, ensuring a neutral hand and wrist positioning during operation (VistaLab Technologies, 2001; Costello, 2005). The Vista Ovation^{R} pipette consists of a 45-degree angled pipette shaft that sticks out from the top of the pipette for tip insertion, a large contact surface and contoured grip surface for comfort, an adjustable finger hook, a separate spring-loaded ejection button, a rotating plunger button/knob for volume adjustment and aspiration and dispensation, and a large volume display window on the body of the pipette (VistaLab Technologies, 2001). The VistaLab ^{TM} Technologies Ovation^{R} pipette model also provides audible feedback for tip insertion and is self-standing (VistaLab Technologies, 2001). The volume range of the pipette is displayed on the plunger/pushbutton and on the base of the pipette, and in this study, the volume range used was 100 microlitres to 1000 microlitres.

Figure 6: An ergonomic mechanical pipette model - Vistalab^{TM} Technologies Ovation^{R} pipette (Image taken from https://vistalab.com/ovation-m-micropipette_post/g).

The technical characteristics of the different pipette models were measured. These included measures of weight, length, and grip circumference and are displayed below:

Table 1: Technical characteristics of two different pipette models. Technical characteristics include weight, length, and grip circumference.

Technical characteristics	Lasec™ AV pipette	VistaLab™ Technologies Ovation® pipette
Weight (g)	98	140
Length (cm)	28,2	15,5
Grip circumference (cm)	10,4	12,6

3.4 Variables of no interest

The pipetting task was standardized (tip insertion, fluid aspiration, fluid dispensation, and tip ejection) and the number of pipette cycles was set at 40 repetitions for each pipette model. The pipetting volume was standardized and set at 1000 microlitres, and water with food colouring was the sample fluid to be pipetted. Participants were allowed to use their preferred method and pace of pipetting during the performance of pipetting tasks (e.g., resting their elbows on the workbench, or not). In addition, participants were allowed to adjust the equipment setup to their preference.

3.5 Dependent variables

This study assessed muscular activity, wrist positioning, time to task completion, and perceptions of effort, comfort, and usability during pipetting tasks completed using two pipette models.

3.5.1 Muscle activity

Surface electromyography (SEMG) was used in this study to measure muscle activity during pipetting. Electromyography (EMG) is an assessment tool that measures neuromuscular electrical activity and is used to observe muscle function (Rash, 1999). The muscle activity measured was used to infer the muscular forces exerted during manual pipetting.

Research shows that during the performance of pipetting tasks, hand and forearm flexor, extensor, and abductor muscles are activated. For this reason, muscle activity of the Abductor Pollicis Brevis (APB), Opponens pollicis (OPP), Abductor pollicis longus (APL), Extensor pollicis brevis (EPB), Extensor pollicis longus (EPL), Flexor pollicis longus (FPL), and Brachioradialis muscles were measured in this study. These muscles were selected with reference to the research reviewed (Lee & Jiang, 1999; Asundi et al., 2005; Lintula & Nevala, 2006; Lu, 2008; Sormunen & Nevala, 2013; Wu et al., 2015; and Selvaraj, 2018). In addition, the above-mentioned muscles were selected with reference to the expected motion activation patterns of the hand-arm structure during pipetting. The positions of these muscles are shown in Figure *7* page 38, Figure 8 page 39, and Figure 9 page 39. Electrodes were placed overlying the APB, OPP, APL, EPB, EPL, FPL, and brachioradialis muscles as later described in the experimental protocol and as shown in Figure 11, page 43.

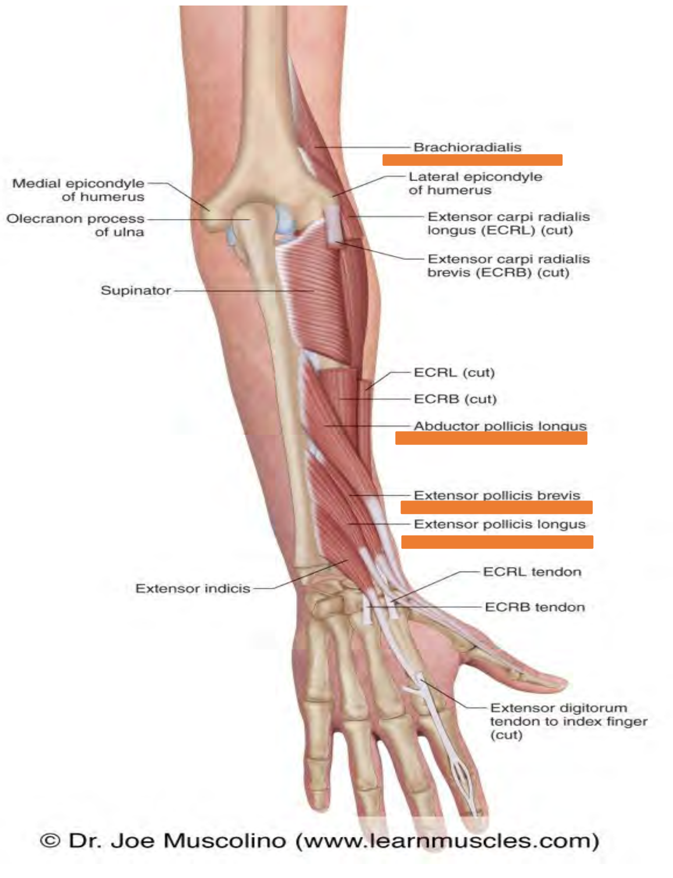

Figure 7: Muscles of the posterior forearm. Muscles of interest are underlined and include the Brachioradialis, Extensor Pollicis Longus, Extensor Pollicis Brevis, and Abductor Pollicis Longus muscles. (Image taken from: https://learnmuscles.com/glosaary/muscles-of-the-posterior-forearm-deep-view).

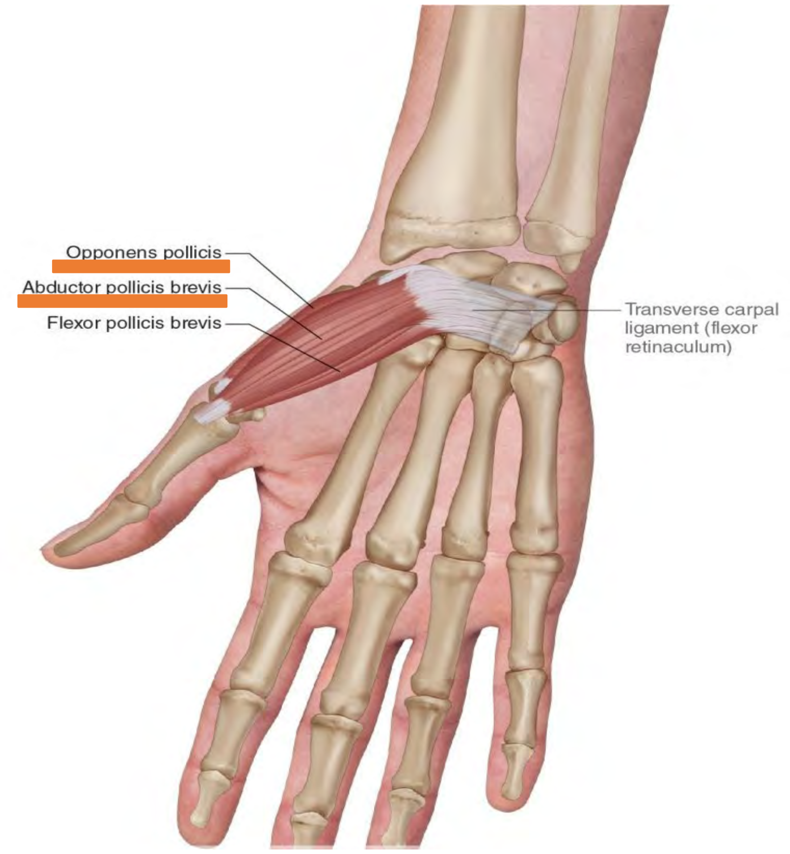

Figure 8: Thenar eminence muscles; Opponens Pollicis (OPP), Abductor Pollicis Brevis, and Flexor Pollicis Brevis (FPB). Muscles used in the study (OPP and APB) are underlined. (Image taken from: https://learnmuscles.com/glossary/thenar-eminence-group/).

Figure 9: The Flexor pollicis longus muscle (Image taken from: https://www.rehabmypatient.com/hand-fingers-thumb/flexor-pollicis-longus).

3.5.2 Wrist position

A bi-axial goniometer was used to measure wrist movements/positions during pipetting. The wrist movements measured included wrist flexion/extension and radial/ulnar deviation. Wrist movements were characterized using the descriptions provided by Lu and colleagues (2008). Wrist flexion was classified as movement toward the palm, whereas wrist extension was movement toward the hand's dorsal (back). Radial deviation was defined as movement toward the thumb while ulnar deviation was defined as movement toward the fifth digit (Lu et al., 2008). The measured wrist movements are shown in Figure 10, page 40.

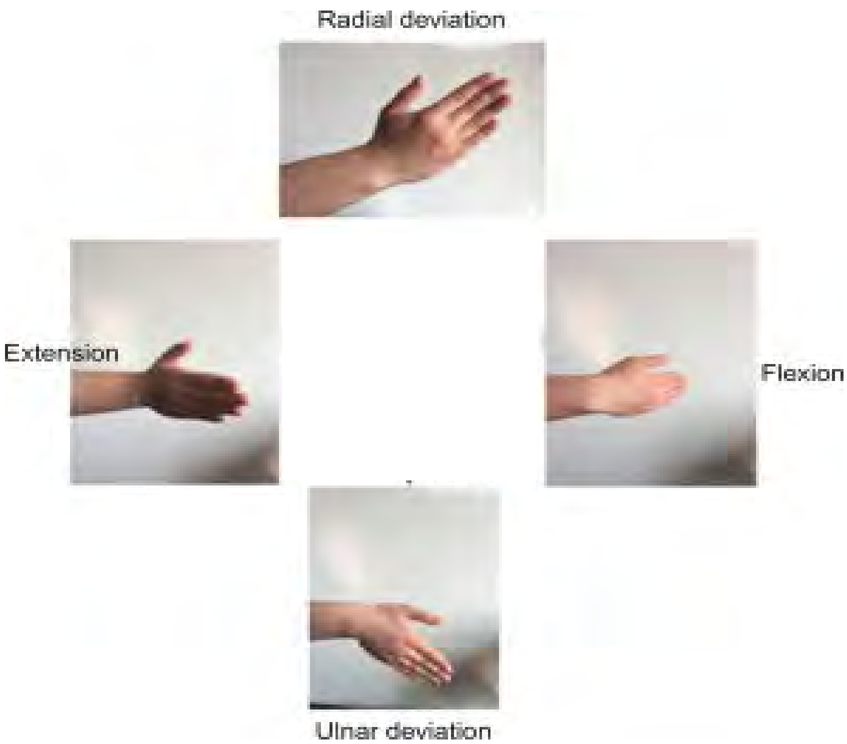

Figure 10: Movements of the wrist, which include wrist flexion, extension, radial deviation, and ulnar deviation. (Image taken from https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.sciencedirect.com%2Ftopics%2Fengineering%2Fradialdeviation&psig=AOvVaw3aPXVIK1o2JLr4SA7E8om8&ust=1675457759720000&source=images&cd=vfe&ved=0CBAQjRxqFwoTCOjhitjc9_wCFQAAAAAdAAAAABAI).

3.5.3 Task completion time

According to Fredriksson (1995) and Lee & Jiang (1999), pipetting requires accuracy, precision, and efficiency. Thus, a change in pipette design should ensure that these properties are maintained or improved. Efficiency, as described by Frøkjaer et al. (2000), refers to the accuracy and completeness with which a task or goal is achieved, and the tools used in achieving that task. Measures of efficiency contribute to the usability of tools, for instance, poorly designed tools result in a loss of efficiency and in turn loss of productivity (Frøkjaer et al., 2000). Efficiency is measured by recording the time taken to complete a task. Thus, in this study, efficiency was measured by recording the time taken to complete the pipetting tasks using each pipette model.

3.5.4 Perceptions of effort, comfort, and usability

Perceptual/self-report measures were recorded to gain a holistic view of the development of MSDs associated with manual repetitive pipetting. Self-report measures on the perception of tasks are indicators of the relationship between tasks and workstation attributes, and enable the identification of tasks, equipment, or workstations with high risks (Krawczyk, 2012). In this study, the Borg Ratings of Perceived Exertion (RPE) scale was used to measure the perceived muscular exertion/effort during the use of manual pipettes.

Subjective ratings on comfort and usability were also recorded to gather information on the comfort and usability of each pipette model. Subjective measures of comfort and usability help assess and mitigate the negative effects of tool design on users and can help determine the point at which tool design impacts performance (Trimmel & Trimmel, 2007). A 5-point Likert scale was used to assess the comfort and usability of various pipette features such as the weight, fit, force application, grip, ease of use, efficiency, and location of operating controls between the different pipette models. These features were assessed as they contribute to the comfort of the tool and affect muscle activity, postures, and contribute to the risk of MSD development associated with tool use (Erickson & Smith, 2007).

As an additional measure of subjective perceptions of the different pipette models, user preference was recorded.

3.6 Tools and Equipment

3.6.1 Surface electromyography

Surface electromyography was measured using rectangular/bar-shaped Ag/AgCl electrodes (22 x 28 mm) with a contact diameter of 10 mm and an inter-electrode distance of 20 mm. Five electrodes were used and placed on the skin surface of the underlying muscles of interest on the pipetting hand and forearm (see Figure 11, page 43). Each electrode was inserted into a corresponding analogue channel on the Biometrics DataLOG W4X to measure muscle activity during pipetting. One electrode was used to measure muscle activity of the Extensor Pollicis Brevis and Abductor Pollicis Longus muscles due to the muscles having similar action lines (see Figure *7*, page 38). The APL muscle was used to represent both muscles throughout the study as it is more prominent and superficial in comparison to the EPB muscle. Similarly, one electrode was used to measure muscle activity of the Opponens Pollicis, and Abductor Pollicis Brevis muscles as the muscles are within close proximity and have similar action lines (see Figure 8, page 39) and using two electrodes for each muscle would cause interference as the electrodes would be too close. To calibrate the EMG electrodes/signal, participants were required to relax their dominant hand and forearm on the side of their body, with their palms facing forward, so that all hand-arm muscles of interest were relaxed, and no activity was recorded on the electromyogram.

A ground electrode was placed over the lateral epicondyle of the forearm on the non-dominant/inactive hand to reduce crosstalk. Muscle activity was recorded using a sampling frequency of 1000 Hz per second and a bipolar electrode configuration. The EMG signal was amplified with pre-amplifiers. The EMG data logger unit was placed on the table while participants performed pipetting tasks. The electrode wires were secured in such a way as to prevent inference with the pipetting task.

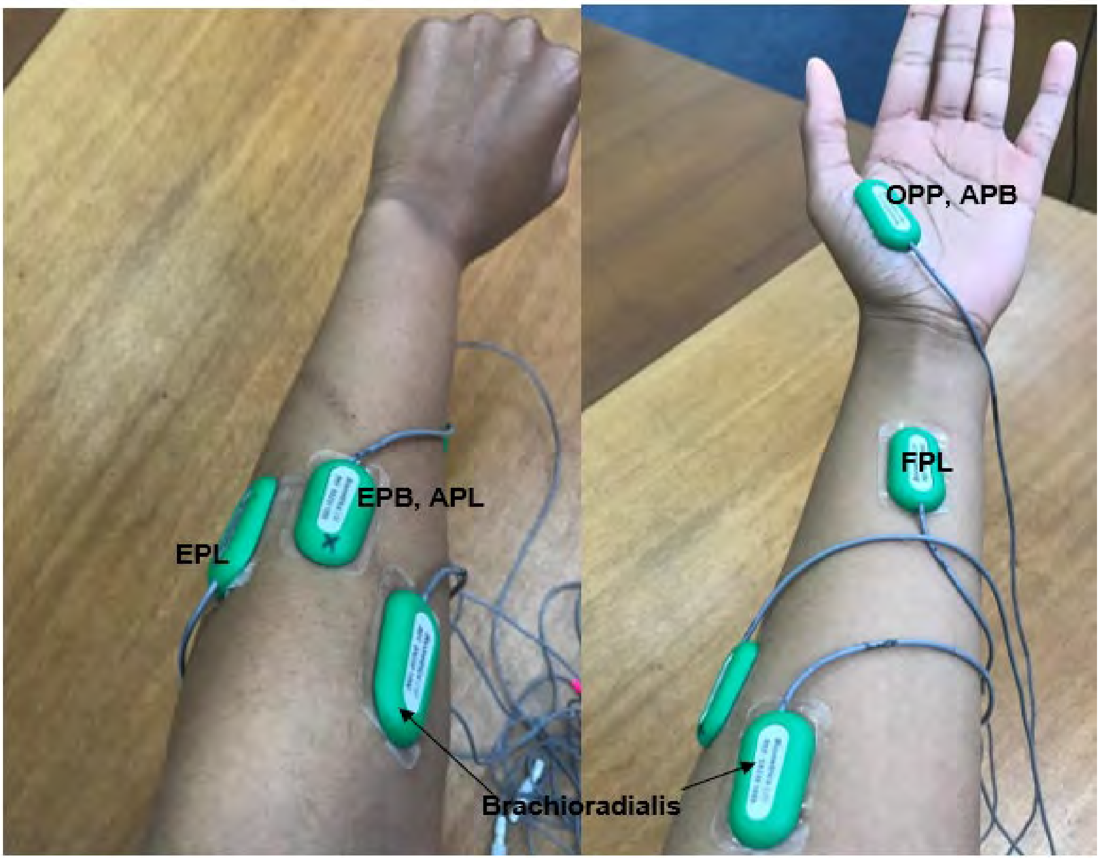

Figure 11: Electrode placement on the surface of EPL, EPB, APL, Brachioradialis, OPP, APB, and FPL muscles.

3.6.2 Bi-axial goniometer

The bi-axial electrogoniometer was placed on the dorsal surface of the participant's dominant hand using adhesive tape. The goniometer end-blocks were secured over the third metacarpal and lower aspect of the forearm (see Figure 12, page 44). Two analogue channels of the Biometrics Ltd DataLOG W4X8 were used to measure wrist posture, whereby one channel recorded sagittal plane movements (flexion and extension) and the other channel recorded frontal plane movements (radial and ulnar deviation). Participants were required to place their dominant hand on a flat surface in a neutral position (palm facing downwards) to calibrate and zero the goniometer end-blocks. The goniometer recordings were sampled at a frequency of 50 Hz per second.

Figure 12: Placement of Bi-axial goniometer on pipetting hand.

3.6.3 Task completion time (Stopwatch)

The time taken to complete the pipetting tasks using each pipette model was measured using a stopwatch application on a mobile phone. The stopwatch was started at the beginning of the first pipette cycle with participants inserting a disposable tip onto the pipette. The end was marked when the last Eppendorf tube was closed, and the disposable tip was ejected.

3.6.4 RPE scale and 5-point Likert scale

The Borg Ratings of Perceived Exertion Scale (RPE) was used to measure the perceived physical exertion during pipetting using the different pipette models. The RPE scale quantifies subjective perceptions of effort, exertion, breathlessness, and fatigue during a physical task (Williams, 2017).

In this study, individuals were required to report on their perceptions of local (muscular) effort using the RPE scale (Appendix A). Local ratings of exertion at the level of the wrist, hand, thumb, and forearm were recorded for each pipette model. These body parts were measured as they are the commonly strained and used regions during pipetting. Central perceptions of cardiovascular and respiratory efforts were not taken into consideration due to the light nature of pipetting, and the low chances of it causing any excessive physiological strain on the individuals.

In addition to the Borg Rating of Perceived Exertion scale, a 5-point Likert scale was used to analyse subjective perceptions of the comfort and usability of each pipette model. Participants were required to answer 10 questions (Appendix B) relating to the comfort, usability, and overall preference of pipette features, by rating their responses to each question from 1 to 5 for each respective pipette model, where 1 represented very uncomfortable and 5 represented very comfortable.

3.7 Participant characteristics

A sample of 20 individuals, including 9 females and 11 males, participated in this study. Participants included Rhodes University Biochemistry, Biotechnology, Microbiology, Chemistry, and Pharmacy students, in their second, third, or postgraduate years of study. Participants were required to have at least one year of practical pipetting experience (individuals who had been exposed to only online-based modes of learning during the Covid-19 pandemic were excluded from this study). Participants were recruited through word of mouth, posters that were posted on social media and WhatsApp groups, as well as emails sent out by the Biological sciences, Pharmacy, and Chemistry department administrators.

All participants were familiar with using pipettes and performing the tasks involved in the pipette cycle (tip insertion, fluid aspiration, fluid dispensation, and tip ejection). Participants also had experience using the traditional pipette model used in this study (Lasec™ AV pipette).

Individuals with current or recurring hand or upper limb injuries were excluded from this study to prevent further injury and to avoid any distortion of the results.

3.8 Ethical considerations

Ethical clearance and gatekeeper approval were obtained from the Rhodes University Human Research Ethics Committee before the experimental study was conducted (reference number 2022-5434-6702). Prior to the commencement of the experimental procedure, participants were informed of the aims, protocols, risks, and benefits of the study as well as ethical considerations relating to anonymity, confidentiality, data management, and feedback. Participants gave verbal and signed consent prior to testing.

The ethical clearance and gatekeeper approval certificate are shown in Appendix D and Appendix E.

3.9 Experimental Set-up

A simulated workstation was set up in the Human Kinetics and Ergonomics department (see Figure 13, page 46). The workstation consisted of a fixed table (height 0,77m) that had sufficient leg room (such that the table provides good knee clearance, and the legs can be stretched under the table), a standard laboratory stool, a Lasec^{TM} AV pipette, a VistaLab^{TM} Technologies Ovation^{R} pipette, tip disposal buckets, pipetting tips, two sample containers, and 80 Eppendorf tubes set on the workbench.

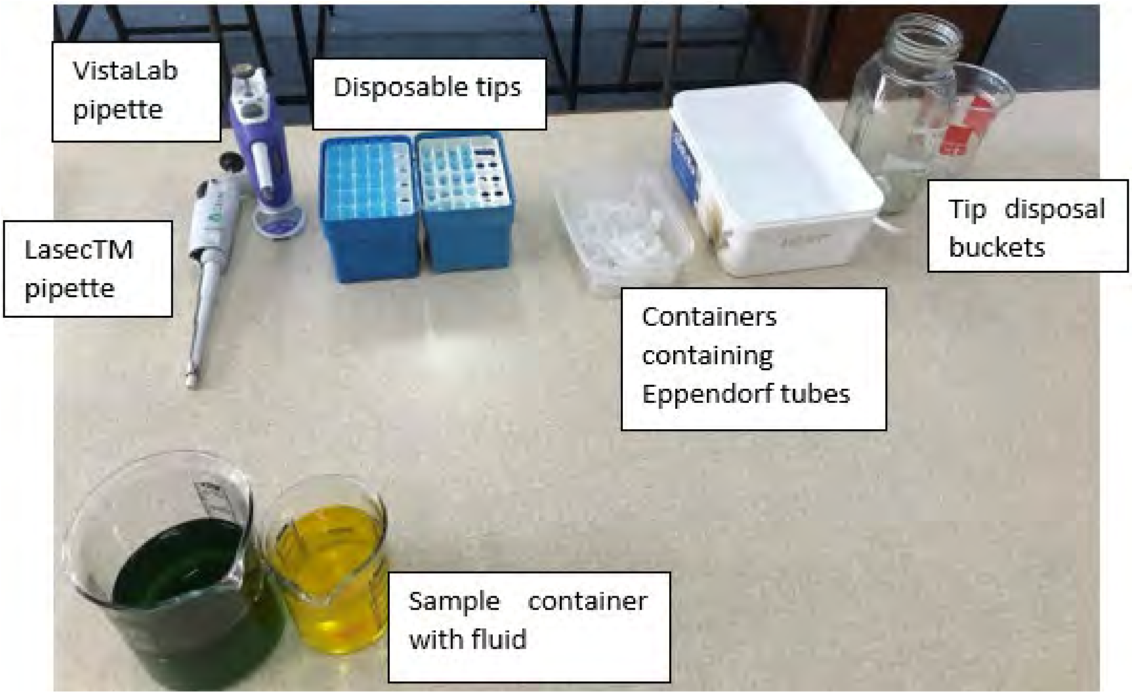

Figure 13: A simulated laboratory workbench/workstation consisting of pipetting apparatus.

3.9.1 Anthropometric measures

Hand anthropometric measures such as hand size help infer the fit between the user's hand and the size of the pipette, which in turn influences grip, performance, and the ergonomics of the pipette (Lee & Jiang, 1999; Sormunen & Nevala, 2013). In addition, Fredriksson (1995), mentions that the degree of thumb flexion/extension is influenced by the length of the thumb and the height of the pipette button. Thus, hand anthropometric measures play an important role in pipette operation, task performance, and influence the muscular strain resulting from tool use.

In this study participants' hand anthropometric data were measured to determine the handle size of the pipettes relative to individual hand sizes. Hand anthropometric measurements were recorded on the dominant hand performing the pipetting task and included measures of hand length, palm length, hand width, palm circumference, thumb length, and hand thickness, as proposed by Mohammad (2005) and as shown in Figure 14, page 47 and Figure 15, page 48. Hand length, palm length, and thumb length were measured using a ruler; hand breadth/width was measured using callipers; and hand thickness and palm circumference were measured using a tape measure. Mohammed (2005) mentions that these hand dimensions are essential parameters for hand tool design. The measurements of the mentioned anthropometric parameters are described in Appendix F.

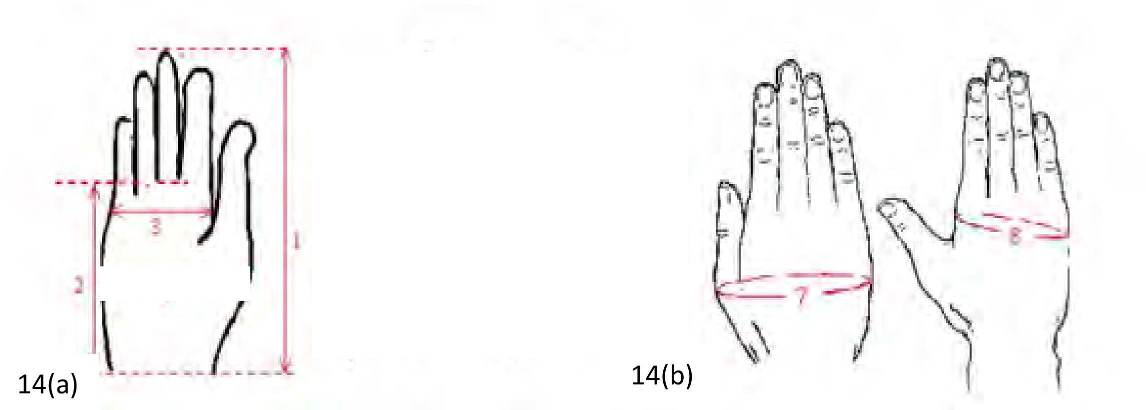

Figure 14: Hand anthropometric measures (Image taken from Mohammed, 2005).

14(a). Hand dimensions 1-3 illustrate measures of 1. Hand length, 2. Palm length, and 3. Hand width.

14(b). Hand dimensions 7-8 illustrate measures of 7. Hand circumference, and 8. Palm circumference.

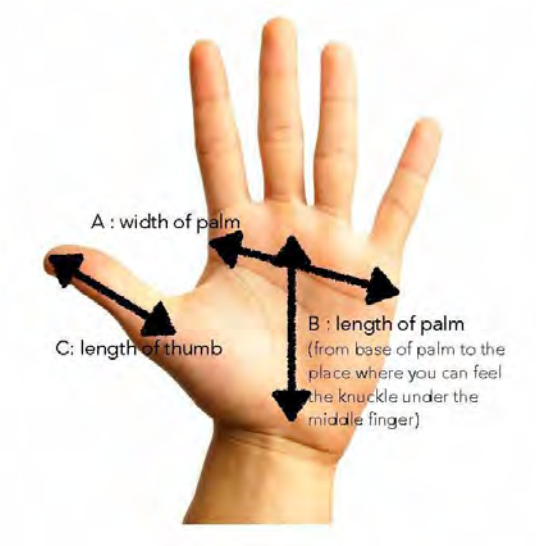

Figure 15: Anthropometric measures of thumb length, palm width, and palm length (Image taken from: https://berkshireknots.wordpress.com/2014/09/16/hand-measurements-for-sizing-of-convertible-mitten-gloves/).

3.10 Experimental procedures

The experimental procedures of this study consisted of two sessions; the information and familiarization session followed by the experimentation session.

3.10.1 Session 1: Information and familiarization

Information

The information session involved informing participants of the purpose, experimental procedures, risks, and benefits of this study verbally and in writing via a letter of information (Appendix G). Participants were also verbally asked for their consent prior to the commencement of the experimental protocol and were required to sign a consent declaration (refer to Appendix H). Demographic and hand anthropometric measures were recorded for each individual, thereafter participants were familiarized with the pipette models and the pipetting task.

Demographic and hand anthropometric measures

Demographic measures included gender, pipetting experience, hand dominance, and questions relating to previous or current hand ailments. This was followed by anthropometric measurements of the hand. Hand length, palm length, hand width, thumb length, palm circumference, and hand thickness were measured as shown in Figure 14, page 47 and Figure 15, page 48.

Equipment and task familiarisation

Participants were then familiarised with the equipment, experimental procedure, and protocol. They were instructed on how to use the different pipette models and how to perform the pipetting task. Participants were required to practice inserting a tip, aspirating a random pre-set volume of water from a sample container, dispensing fluid into an Eppendorf tube, and ejecting the tip using each pipette model. The pipetting familiarisation task was repeated using each of the pipette models until participants felt comfortable with using each model. This was to allow participants to familiarize themselves with each pipette model and their functions and to reduce the negative impact that unfamiliarity with the task and tools may have on the results.

3.10.2 Session 2: Testing

Maximal Voluntary Exertions (MVEs)

To measure muscle activity, maximal voluntary exertions (MVEs) of each muscle of interest were measured. The MVE's were used to relativize the activity of the respective muscles during the performance of pipetting tasks in order to normalize the EMG signal and determine relative changes in muscle effort using the different pipette models.

Prior to testing, the skin surface area above the muscles of interest was abraded and cleaned using alcohol. Individuals with excessive hair at the regions of interest were shaved to reduce signal interference and to prevent pain upon the removal of the electrodes. The muscles of interest (Opponens pollicis, Extensor Pollicis Brevis, Abductor Pollicis Longus, Extensor Pollicis Longus, Flexor Pollicis Longus, and Brachioradialis) were located by referring to protocols recommended by Kendall (2005), and Gross et al. (2009). The electrodes were attached to the skin surface of the muscles of interest and secured using adhesive tape (refer to Figure 11, page 43 and Appendix Z). Participants were required to perform various limb movements, as proposed by Kendall et al. (2005) and Gross et al. (2009) as shown in Table 2, page 51 to measure the MVE for each muscle. Resistance was applied in the opposite direction to the muscle contraction, as the participant exerted maximal contractions.

Five maximal efforts, each lasting 5 seconds were performed for each of the muscles tested. Rest intervals of 3 to 5 seconds were allowed between each MVE recording, and 10-second rest intervals were allowed between MVE recordings of each muscle.

The participants were encouraged and motivated to exert maximal force while caution was maintained to prevent injury. Following the MVE recordings, goniometer end-blocks were placed and secured on the dorsal surface of the dominant/pipetting hand.

Table 2: Postures and actions performed during the maximum voluntary exertion protocols as proposed by Kendall et al. (2005) and Gross et al. (2009).

Muscle	**Maximum voluntary test**
Abductor pollicis Brevis	With the hand stabilized, the participant abducts their thumb ventrally from the palm. The researcher applies pressure against the proximal phalanx in the direction of adduction toward the palm.
Opponens pollicis	The hand is stabilized while the metacarpal bone of the thumb is flexed, abducted, and slightly medially rotated so that the thumbnail shows in the palmar view. Resistance is applied against the metacarpal bone in the direction of extension and adduction with lateral rotation.
Flexor Pollicis Longus	The participant's hand is rested on the table for support, with the metacarpal bone stabilized and the proximal phalanx of the thumb in extension. The participant flexes the interphalangeal joint of the thumb. The tester applies pressure against the palmar surface of the distal phalanx in the direction of extension.
Flexor Pollicis Brevis	The metacarpophalangeal joint of the thumb is flexed without flexing the interphalangeal joint. Resistance is applied against the palmar surface of the proximal phalanx in the direction of extension.
Extensor Pollicis Longus	The participant's hand is stabilized while the examiner applies counterpressure against the palmar surface of the first metacarpal and proximal phalanx. The participant extends the interphalangeal joint of the thumb. Pressure is applied against the dorsal surface of the interphalangeal joint of the thumb in the direction of flexion.
Extensor Pollicis Brevis	The wrist is stabilized while the participant extends the metacarpophalangeal joint of the thumb. The examiner applies pressure against the dorsal surface of the proximal phalanx in the direction of flexion.
Abductor Pollicis Longus	The wrist is stabilized while the participant abducts and slightly extends the first metacarpal bone. Pressure is exerted against the lateral surface of the distal end of the first metacarpal in the direction of adduction and flexion.
Brachioradialis	The examiner places one hand under the participant's elbow to cushion it from the table. The participant then flexes the elbow with the forearm neutral between pronation and supination. The belly of the brachioradialis must be seen and felt during this movement because the movement can also be produced by other muscles that flex the elbow. The examiner applies pressure against the lower forearm in the direction of extension.

Experimentation

Participants were required to perform the pipette cycle using their dominant hand. The pipette cycle included four main actions, namely tip insertion, fluid aspiration, fluid dispensation and blowout, and tip ejection. These actions are shown in Figure 1 page 8, and Figure 16 page 53, and described in section 2.5.3 page 23.

In this study, the pipetting task included participants obtaining an Eppendorf tube from a container with their non-dominant hand, performing the pipette cycle using the respective pipette model with their dominant hand, closing the Eppendorf tube with their non-dominant hand, and then placing it into a container (refer to Figure 16, page 53). This was repeated 40 times so that 40 separate Eppendorf tubes were filled with sample fluid. While participants were repeatedly performing the pipetting cycle, EMG, and joint angles were recorded, as was the time taken to completion. Following the completion of the pipetting task with one pipette model, participants were required to rate their perception of exertion at the level of the hand, thumb, wrist, and forearm using the RPE scale (Appendix A), as well as rate the level of comfort, usability, and preference using the 5-point rating scale (Appendix B).

This same procedure was repeated for the second pipette model so that a total of 80 Eppendorf tubes were filled with fluid. The order of using the two pipettes was alternated. Furthermore, to prevent local muscle fatigue, 5–10-minute break intervals were allowed when pipette models were switched. Participant responses were recorded on a data sheet (see Appendix I).

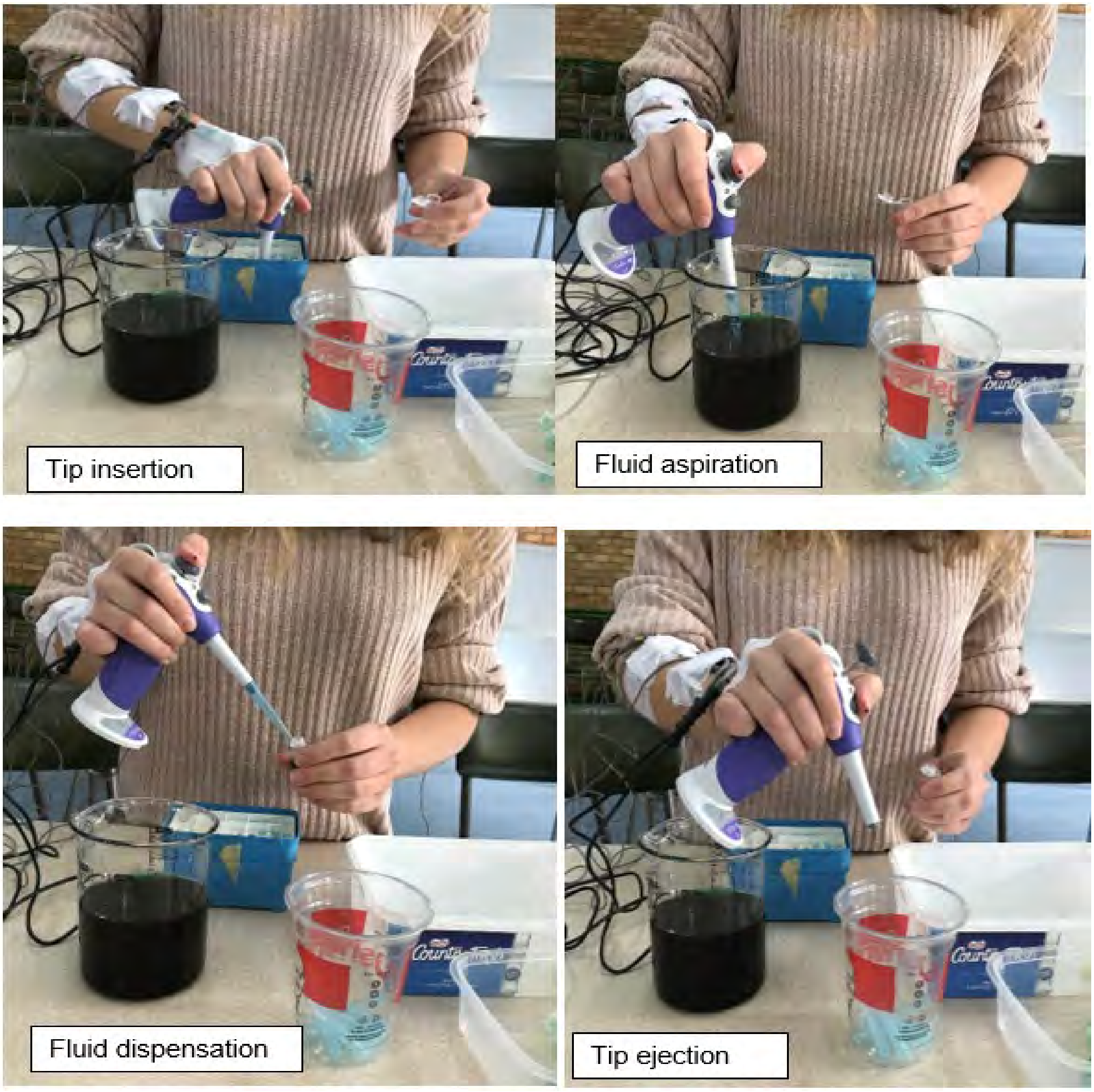

Figure 16: Image of pipetting task performed using the ergonomic pipette model. The pipetting task included, tip insertion, fluid aspiration, dispensation, and tip ejection.

3.11 Data Processing

3.11.1 Muscle activity

Muscle activity during pipetting and Maximal voluntary exertions of the muscles of interest (Opponens Pollicis, Abductor Pollicis Brevis, Flexor Pollicis Longus, Extensor Pollicis Longus, Extensor Pollicis Brevis, Abductor Pollicis Longus, and Brachioradialis) were processed as shown in Figure 17, page 54.

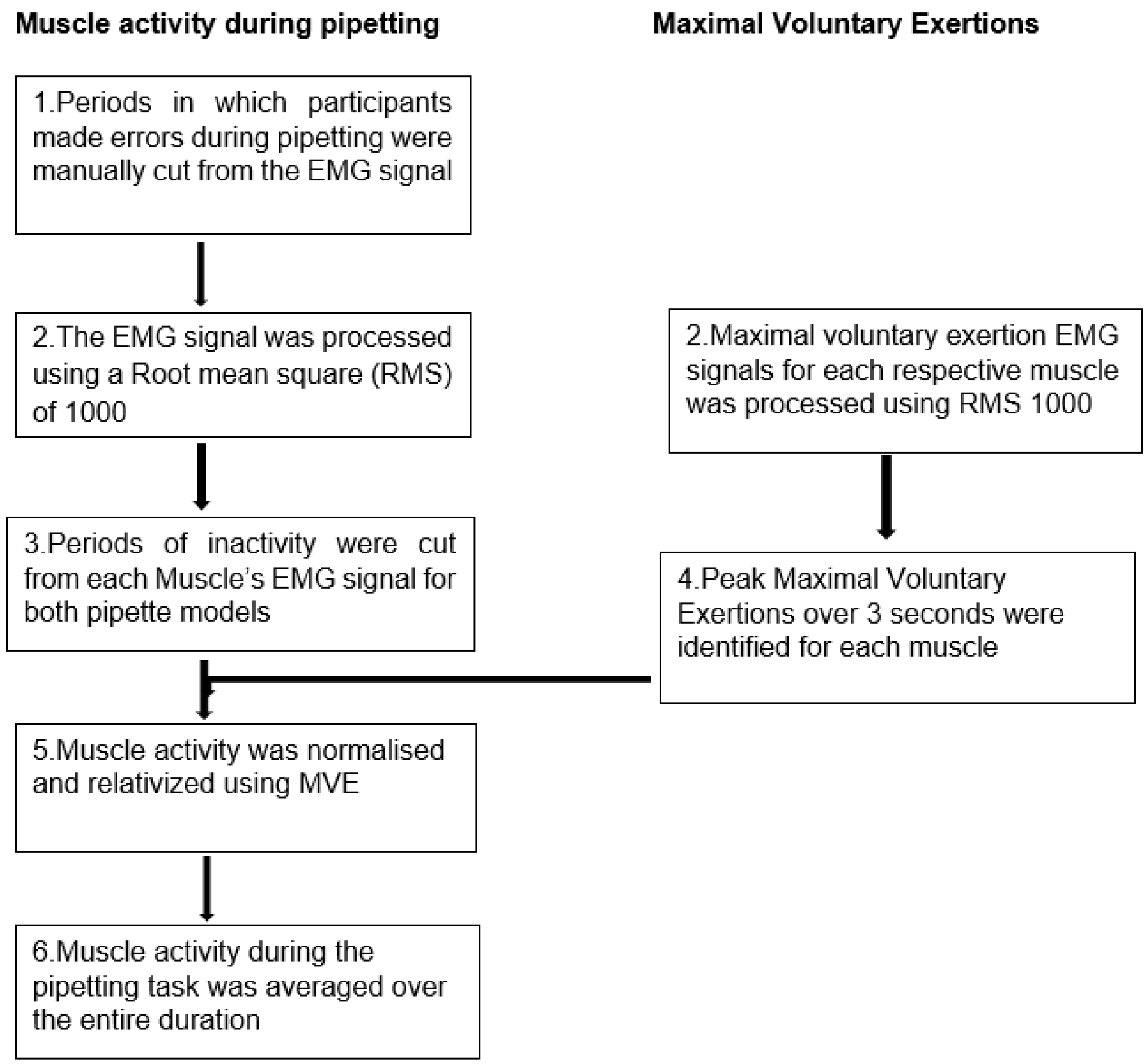

Figure 17: Data processing steps used to process muscle activity responses during pipetting and maximal voluntary exertions.

1. The electromyograms of all the muscles of interest during the completion of each pipetting task were analysed, and periods which participants made errors during the pipetting task (i.e., ejecting before dispensing fluid) were manually cut from the signal. In addition, the first three and the last three pipetting cycles were cut from the EMG signal.
2. The EMG signal during pipetting was then processed and filtered using the Root-mean-square (RMS) over 1000 milliseconds. This was done to reduce the signal to a waveform that is easier to analyse and to obtain information about the amplitude of the signal, which is an indication of the power and physiological activities of the motor units during muscle contraction. The MVE's for each

muscle were also processed and filtered using the RMS over 1000 milliseconds.

3. Periods of muscle inactivity were cut from each respective muscle signal by identifying a muscle (OPP, APB) which clearly showed periods of inactivity, and setting those periods as the cut-off threshold. Muscle activity signals below the threshold of inactivity of the OPP, APB muscles were cut from all muscles. The threshold was identified individually for each participant and each pipette model. (Threshold values can be found in Appendix J).
4. Maximal Voluntary Exertions were recorded over a period of 5 seconds for each muscle and repeated 5 times. MVE signals of each muscle were processed by identifying a signal with the highest activity (amplitude) out of the 5 repetitions and selecting 3 seconds of that signal to determine the maximal activity for the respective muscle.
5. The EMG signal during pipetting was normalised by relativizing muscle activity of each muscle to the MVE for that respective muscle. Muscle activity was recorded as a percentage of MVE.
6. The average muscle activity was calculated for the entire duration of each pipetting task.

3.11.2 Wrist position

Goniometer readings were recorded and processed for the entire duration of each pipetting task. The goniometer measures were processed as shown in Figure 18, page 56.

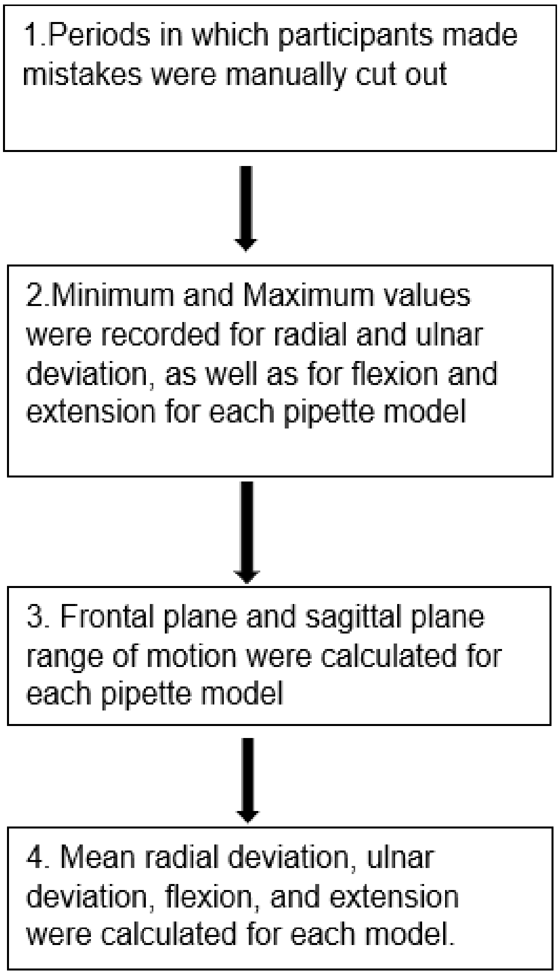

Figure 18: Data processing steps used to process goniometer readings of wrist postural responses.

1. Periods which participants made errors during the performance of the pipetting tasks were manually cut from the goniometer readings.
2. The minimum and maximum values for radial and ulnar deviation, as well as for wrist flexion and extension were recorded over the period of the entire pipetting task duration.
3. Sagittal plane Range of Motion (ROM) was calculated by subtracting maximum radial/ulnar deviation from minimum radial/ulnar deviation, and frontal plane

ROM was calculated by subtracting maximum flexion/extension from minimum flexion/extension. This was done for both pipette models.

4. Average radial deviation, ulnar deviation, flexion, and extension were recorded by classifying the minimum and maximum values into the respective wrist positions. Minimum (negative values) represented radial deviation and wrist extension, and maximum (positive values) represented ulnar deviation and wrist flexion. These were calculated for both pipette models.

3.12 Statistical Analysis

The recorded measures were analysed using descriptive and inferential statistics. Statistical analysis of the data was processed as shown in Figure 19, page 57.

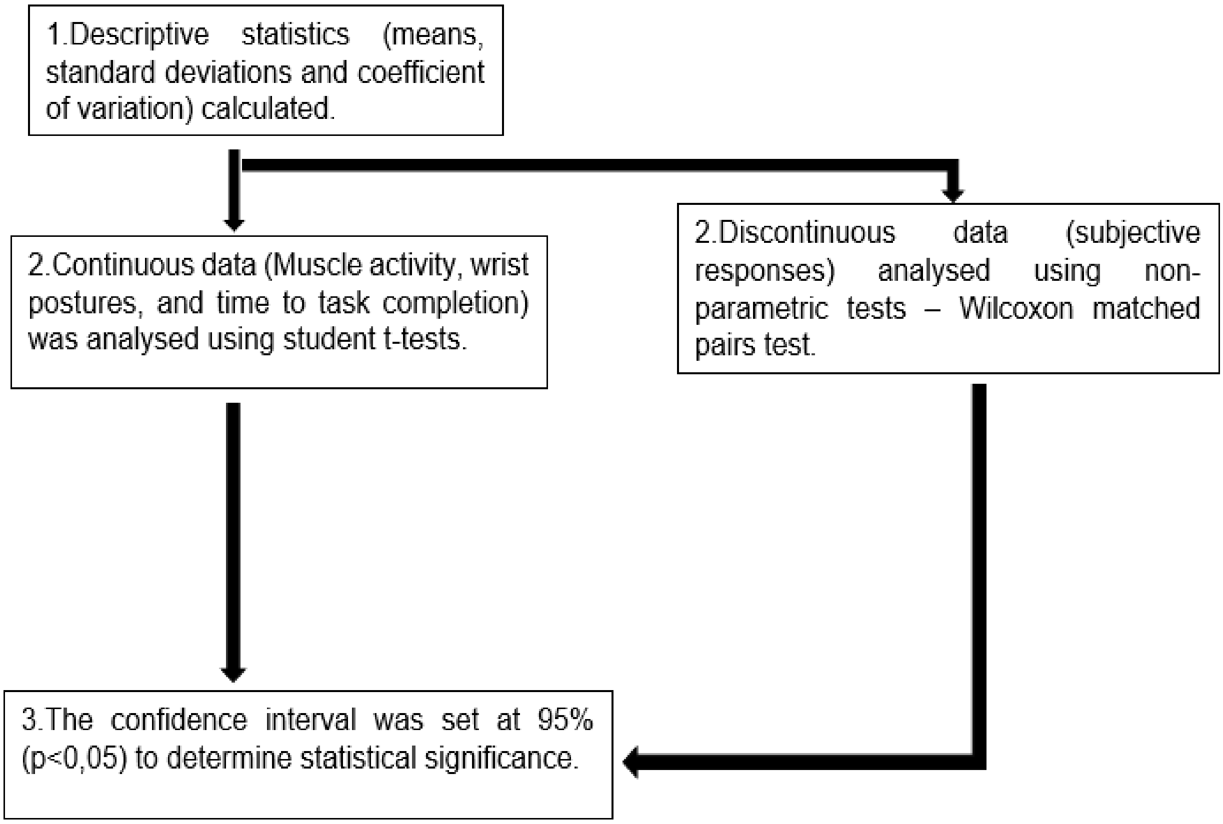

Figure 19: Statistical analysis method used to analyse dependent variables.

1. Descriptive statistics were calculated for all experimental data (Demographics, anthropometrics, muscle activity, wrist postures, time to task completion, RPE responses, and questionnaire responses). Means, standard deviations, and coefficients of variation were calculated for these measures.

2. Muscle activity, wrist postures, and time to task completion measures (continuous data) for each pipette model were treated using student paired t-tests. Muscle activity responses of each muscle, time to task completion, as well as goniometer responses (frontal plane and sagittal plane ROM, radial and ulnar deviation, and flexion and extension) for the traditional pipette were paired and compared with the corresponding responses for the ergonomic pipette model.

   The Wilcoxon signed-ranked test, a non-parametric test, was used to analyse subjective responses (RPE and questionnaire responses) due to the data being discontinuous and categorical. RPE responses at the level of the hand, thumb, wrist, and forearm as well as questionnaire responses of the traditional pipette model were paired and compared to the corresponding subjective responses of the ergonomic pipette model.
3. The confidence interval was set at 95% ($p<0,05$) for the continuous and discontinuous data to determine statistical significance of the objective and subjective responses between the two pipette models.

3.13 Correlations

Statistical correlations were performed for hand anthropometric measures to determine the effect of hand anthropometry on muscle activity and perceived exertions during the use of the two pipette models. The correlations were as follows:

- Hand anthropometric measures were correlated with corresponding hand anthropometric measures.
- Hand anthropometric measures were correlated with Ratings of Perceived exertions at the level of the hand, thumb, wrist, and forearm for both pipette models.
- Hand anthropometric measures were correlated with questionnaire responses of the two different pipette models.
- Hand anthropometric measures were correlated with Muscle activity responses of the OPP, APB; FPL; EPL; APL, EPB; and Brachioradialis muscles for the traditional pipette model and the ergonomic pipette model.

Correlation tables are found in Appendix V, Appendix W, Appendix X, and Appendix Y.

Chapter 4

Results

Introduction

This chapter will focus on the results of the ergonomic assessment of the different pipette models. The first section of the chapter will deal with the demographic and anthropometric data, followed by biomechanical data including muscle activity and wrist posture responses in section two. The third section will then focus on performance outcomes, specifically the time taken to complete pipetting tasks using the different pipette models. Thereafter, section four covers subjective responses, including measures of perceived exertion, comfort and usability, and user preference. The fifth section of this chapter will focus on cross correlations between anthropometric data with dependent variables. Section six includes a summary of the results, and the last section covers the responses to the research hypotheses.

The confidence level was set at 95% ($p<0.05$) for all the results. Significant results (where $p<0.05$) were highlighted in red on tables and marked with a blue Asterix on graphs. Standard deviations were illustrated as error bars on graphs. Data was presented as Mean ± SD (CV%) in tables. Throughout the results section, the traditional pipette model is referred to as Lasec and the ergonomic model is referred to as Vista.

4.1 Demographics and anthropometric data

This study consisted of 20 participants, of which 11 were males and 9 were females. Participants had an average of 2 years pipetting experience (± 1,92), and 17 of the participants were right-hand dominant whereas 3 of the participants were left-hand dominant. Participants in this study had no hand ailments, and those with previous hand injuries had minor injuries which had subsided.

Table 3: Demographics and hand anthropometric results (n = 20)

Anthropometric measure	Mean
Hand Length (mm)	187,75 ± 10,51 (6%)
Palm Length (mm)	91,625 ± 5,77 (6%)
Hand Width (mm)	80,22 ± 6,77 (8%)
Palm circumference (mm)	204,55 ± 19,11 (9%)
Thumb Length (mm)	65,975 ± 5,58 (8%)
Hand Thickness (mm)	228,9 ± 15,70 (7%)
Pipetting experience (years)	2,6917 ± 1,92 (71%)

4.2 Biomechanical responses

4.2.1 Muscle Activity

Given that manual pipetting results in increased muscular loading, especially of the hand-arm muscles, muscle activity of the Abductor Pollicis Brevis (APB), Opponens Pollicis (OPP), Flexor Pollicis Longus (FPL), Extensor Pollicis Brevis (EPB), Abductor Pollicis Longus (APL), and Brachioradialis (BRACH) muscles was recorded during the performance of pipetting tasks using two different pipette models. The muscle activity responses were normalised using maximal voluntary exertion (MVE) values of each respective muscle to infer muscle force. Thus, muscle activity responses were presented as a percentage of MVE.

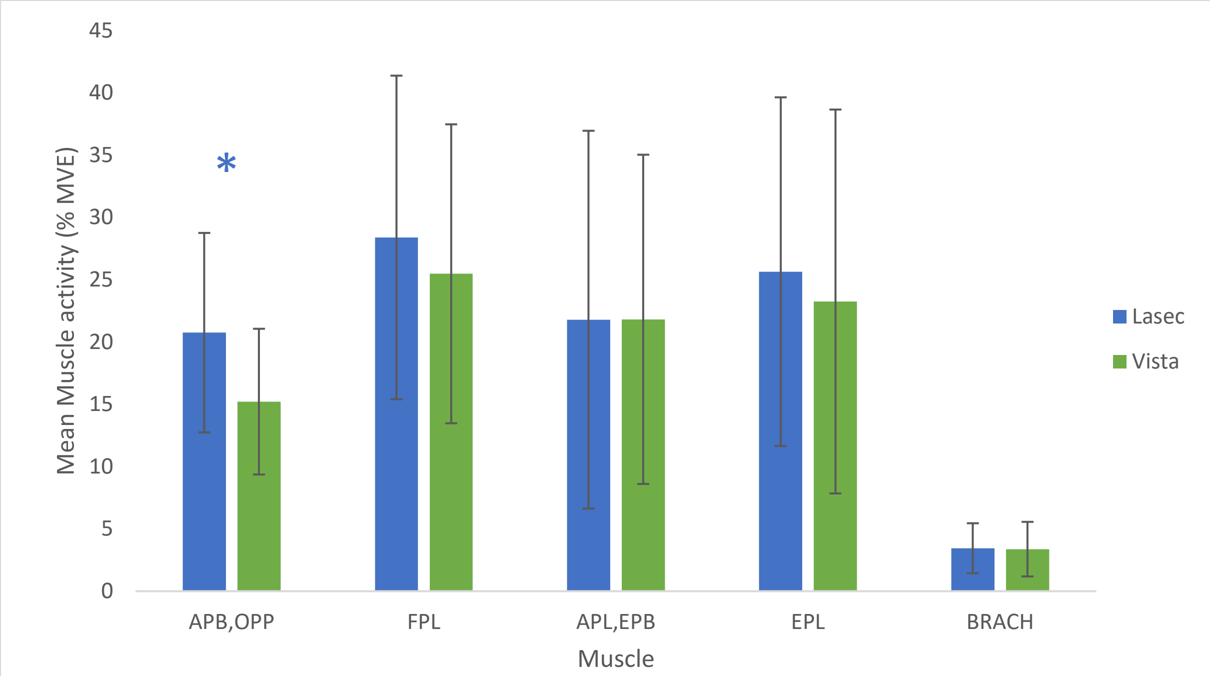

Figure 20: A comparison of the mean (and standard deviation) muscle activity responses between a traditional pipette model (Lasec) and an ergonomically designed pipette model (Vista). Muscles include APB, OPP; FPL; APL, EPB; EPL; and Brachioradialis. (* denotes a statistically significant difference, $p < 0.05$).

Pipette design had a significant effect on the muscle activity of the Thenar eminence muscles (APB, and OPP) (refer to Figure 20, page 61), detailed statistics can be found in Appendix K. The ergonomic pipette model (Vista) significantly reduced muscle activity of the APB and OPP muscles (15,22% ± 5,5) in comparison to the traditional model (Lasec) (20,75% ± 8). The thenar eminence muscles are involved in thumb flexion and abduction, movement that is important during the manipulation of the pipette plunger.

No significant differences were observed between the muscle activity of the other muscles (FPL, APL, EPB, EPL, and Brachioradialis) for the two pipette models (refer to Appendix A). The level of significance for the FPL muscle was 0,09, so an increase in sample size might result in a significant difference. In Addition, the Flexor Pollicis Longus muscle was found to have the highest muscle activity in comparison to other muscle groups. The brachioradialis muscle was found to have the lowest activity for both pipette models (see Figure 20, page 61) indicating that it was not used as much during pipetting. The coefficient of variation for muscle activity of all the muscles was high, highlighting a high variability in muscular loading during pipetting using both pipette models (see Appendix L).

4.2.2 Wrist posture

The use of traditional mechanical pipette models has been associated with awkward wrist postures, which are problematic and increase the risk of Repetitive Strain Injuries placed on pipette users such as Carpal Tunnel syndrome.

In this study, wrist posture was measured using a bi-axial goniometer while participants performed pipetting tasks using two different pipette models. Wrist range of motion, radial and ulnar deviation as well as flexion and extension were measured for each pipette model. This was done to assess and compare the wrist postures assumed and the strain between the traditional pipette model and the ergonomic pipette model.

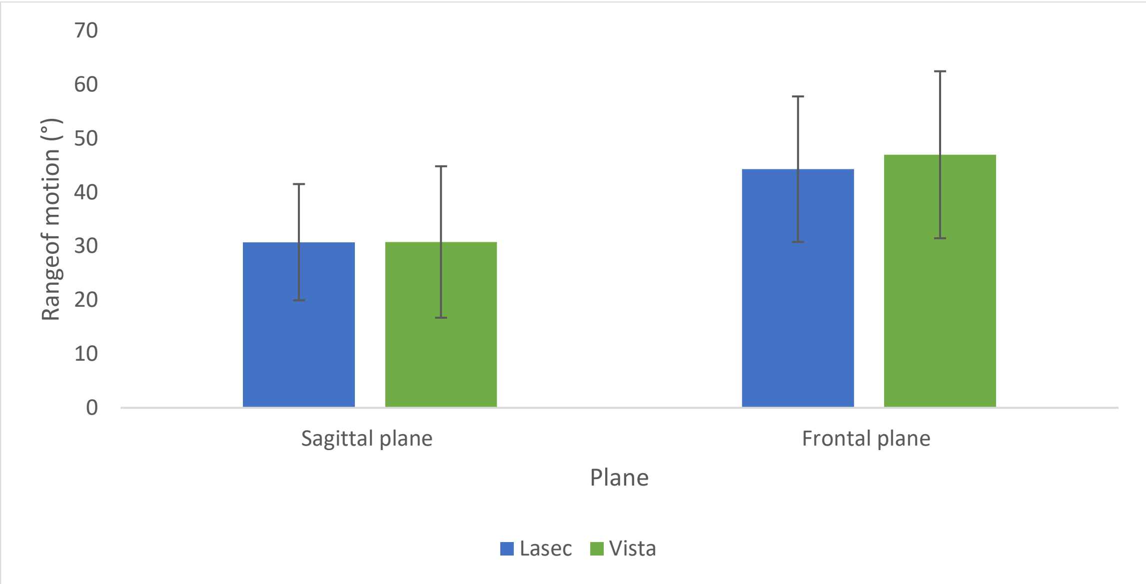

Figure 21: A comparison of mean wrist sagittal plane and frontal plane Range of motion (ROM) between a traditional pipette model (Lasec) and an ergonomic pipette model (Vista).

Wrist range of motion (ROM) during the use of the traditional pipette model and the ergonomic pipette model were assessed and compared. Wrist ROM along the sagittal plane, and ROM along the frontal plane, were similar between the Lasec model and the Vista model (see Figure 21, page 62). No significant differences were found in the ROM responses between the Lasec and Vista pipette models (see Appendix M). Thus, pipette model was found to have no effect on wrist range of motion.

Although wrist range of motion was similar for both pipette models, individual wrist movements along each plane were assessed and compared for each pipette model. Wrist movements/positions included radial deviation, ulnar deviation, flexion, and extension.

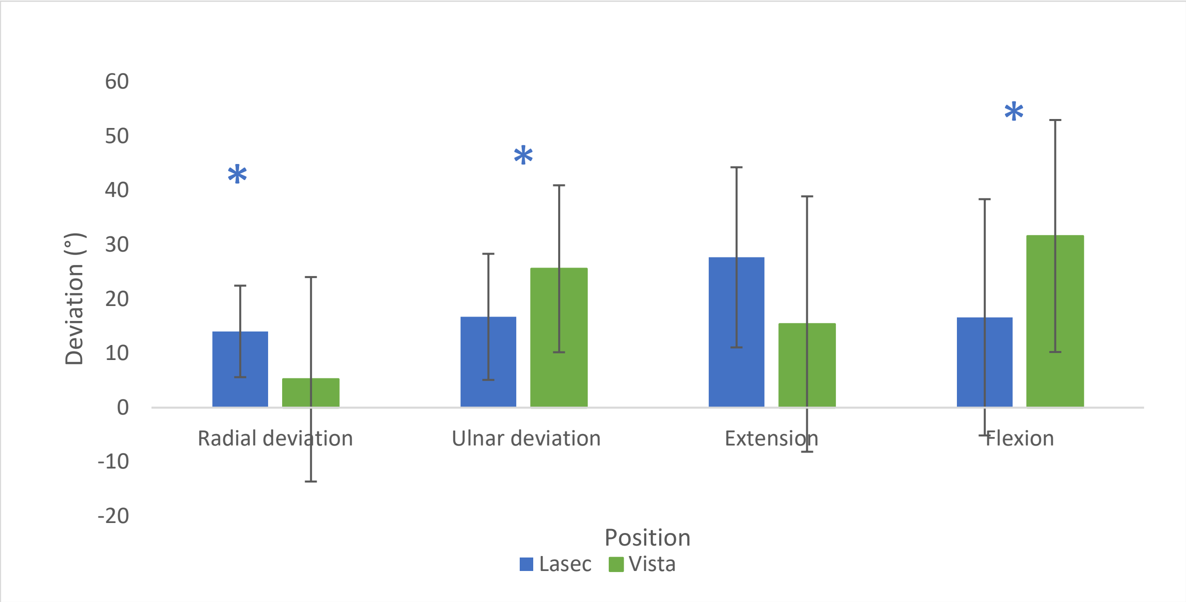

Figure 22: Mean wrist postural angles (with standard deviation) of radial deviation, ulnar deviation, flexion, and extension between a traditional pipette model (Lasec) and an ergonomic pipette model (Vista). (* denotes significant difference $p<0.05$).

Pipette design was found to influence wrist postures assumed during the performance of pipetting tasks (see Figure 22, page 63). Significant differences were found ($p<0.05$) between the radial deviation, ulnar deviation, and wrist flexion responses of the two pipette models. Detailed statistical results of the wrist postural responses are shown in Appendix N.

The ergonomic pipette model (Vista) significantly increased ulnar deviation (25,57 ± 15,37°) and wrist flexion (31,60 ± 21,35°) in comparison to the traditional pipette model (16,72 ± 11,61° ulnar deviation and 16,63 ± 21,74° flexion). Whereas the Lasec model resulted in a significant increase in radial deviation (14,04 ± 8,42°) when compared to the Vista model (5,22 ± 18,82°) (see Figure 22, page 63 and Appendix O). The level of significance for wrist extension was 0,061, so an increase in sample size might generate a significant difference (see Appendix N).

The results show that the ergonomic pipette model might be favourable at reducing radial deviation during pipetting, however the pipette model does not reduce ulnar deviation and wrist flexion. In addition, it was found that both pipette models resulted in a large variation in wrist joint movements (Vista radial deviation (360,53%) and Vista extension (152,74%); Lasec wrist flexion (130,75%)), indicating variability in the postures assumed during pipette operation (see Appendix O).

4.3 Performance responses

4.3.1 Time to task Completion

To assess the efficiency of each pipette model, the time taken to complete pipetting tasks using each pipette model was measured using a stopwatch. The time to task completion was recorded in seconds.

Table 4: Mean time (standard deviation and coefficient of variation) taken to complete pipetting tasks using a traditional pipette model (Lasec) and an ergonomic pipette model (Vista). Results presented as Mean ± SD (CV%).

Pipette model	**Time (s)**
Lasec	428,45 ± 123,70 (28,87%)
Vista	412,65 ± 108,34 (26,25%)

Pipette model design was found to have no significant effect on performance, statistical results are displayed in Appendix P. The time taken to complete pipetting tasks using each pipette model was similar, thus indicating that a change in pipette design had no effect on user performance. However, a large standard deviation was observed in the time taken to complete pipetting tasks for both pipette models (Lasec SD= 123,70 and Vista SD=108,34) (see Table 4, page 64).

4.4 Subjective responses

Subjective responses were recorded for each pipette model and included measures of exertion, comfort and usability.

4.4.1 Ratings of perceived Exertion

Local (muscular level) Ratings of Perceived Exertion (RPE) were recorded to infer on participant's perceived muscular effort required to operate the different pipette models. RPE ratings were recorded at the level of the hand, wrist, thumb and forearm for the traditional pipette model and the ergonomic pipette model following the completion of pipetting tasks. These body regions were measured due to their frequent exposure to stressors during pipette operation. RPE responses of the traditional model were paired and compared with the RPE ratings of the ergonomic model (refer to Appendix Q).

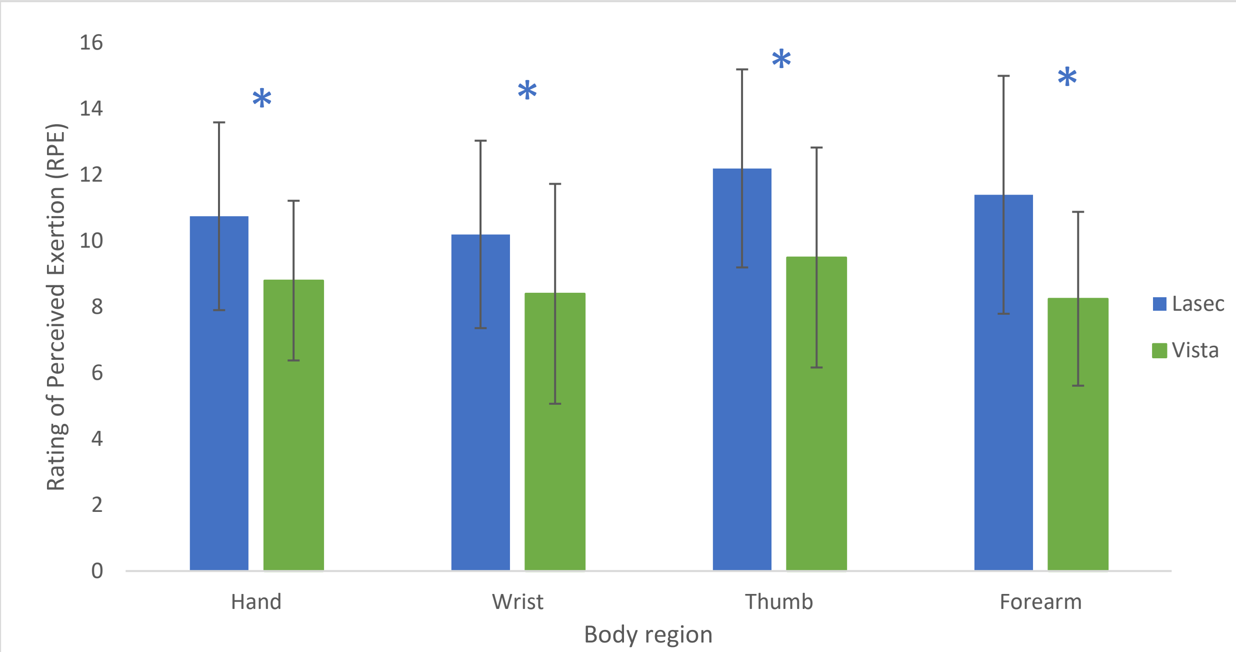

Figure 23: A comparison of the mean (and standard deviation) Ratings of Perceived Exertion (RPE) responses between a traditional pipette model (Lasec) and an ergonomic pipette model (Vista). RPE ratings included ratings relating to the hand, wrist, thumb, and forearm. (* denotes a statistically significant difference ($p<0.05$).

Pipette design was found to significantly affect user's perceived exertion at the level of the hand, wrist, thumb, and forearm (see Figure 23, page 65), statistical results are shown in Appendix Q. The Vista model was perceived to require significantly lower muscular effort of the hand, wrist, thumb, and forearm in comparison to the Lasec model. The forearm was perceived to exert the least effort during the operation of the Vista model (refer to Figure 23, page 65).

Whereas, the traditional pipette (Lasec) model was perceived to require significantly higher levels of muscular exertion, especially of the thumb (12,2 ± 3), forearm (11,4 ± 3,60), and hand (10,75 ± 2,84) (see Appendix R and Figure 23, page 65). Although the mentioned ratings correspond to a descriptor of being Light to somewhat hard, this indicates that the perceived exertion during pipetting is not very high however, prolonged use of the traditional pipette could increase the risk of pipette operators experiencing pain or discomfort, and the development of MSDs.

The results also reveal that the thumb was perceived to exert the most effort during the operation of both pipette models. However, the Vista model was perceived to require less thumb effort (9,5 ± 3,33) in comparison to the Lasec model (12,2 ± 3).

4.4.2 Comfort and Usability responses

A questionnaire with 10 questions relating to pipette features was used to assess and compare the comfort and usability between two different pipette models. Participants were required to answer each question using a 5-point Likert scale with verbal anchors, where 1 represented very uncomfortable and 5 represented very comfortable. Pipette features assessed included pipette grip, location of aspiration and dispensation plunger, task performance using pipette, tip application, location of ejection button, tip ejection, thumb force for plunger manipulation, fit in hand, weight in hand, and overall comfort and efficiency. Participants were required to answer all 10 questions for the traditional pipette model, and the ergonomic pipette model.

To present the results, the questionnaire was divided into two categories namely design-related features (which included pipette grip, location of plunger, fit in hand, weight in hand, and location of ejection button) and task/performance-related features (which included ease in performing task using the pipette, tip application, tip ejection, thumb force for plunger manipulation, and overall comfort and efficiency). The number of responses were tallied and grouped into the respective comfort ratings for each question to determine and compare the cumulative frequency of comfort responses for each pipette model's feature.

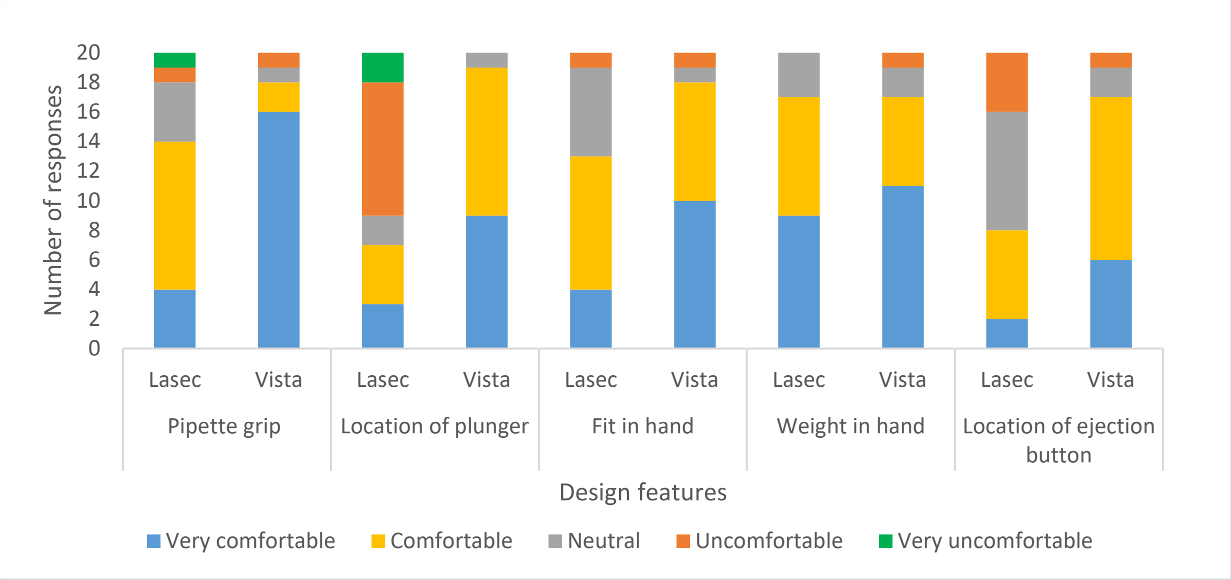

Figure 24: A comparison of the frequency of comfort ratings for the design-related features between a traditional pipette model (Lasec) and an ergonomically designed pipette model (Vista).

It was found that majority of the participants found the design-related features of the ergonomic pipette model (Vista) more comfortable than those of the traditional pipette model (Lasec) (see Figure 24, page 67). Features such as the location of the plunger, and location of ejection button were found to be less comfortable in the traditional pipette model in comparison to the ergonomic pipette model. The location of the plunger of the Lasec model was found to be the least comfortable feature of the pipette model, as 55% of the participants rated it as uncomfortable to very uncomfortable. In contrast, the location of the plunger of the Vista model was found to be the most comfortable feature of the pipette model (95% of users rated it from comfortable to very comfortable) (refer to Figure 24, page 67). In addition, 80% of users found the grip of the ergonomic pipette model very comfortable.

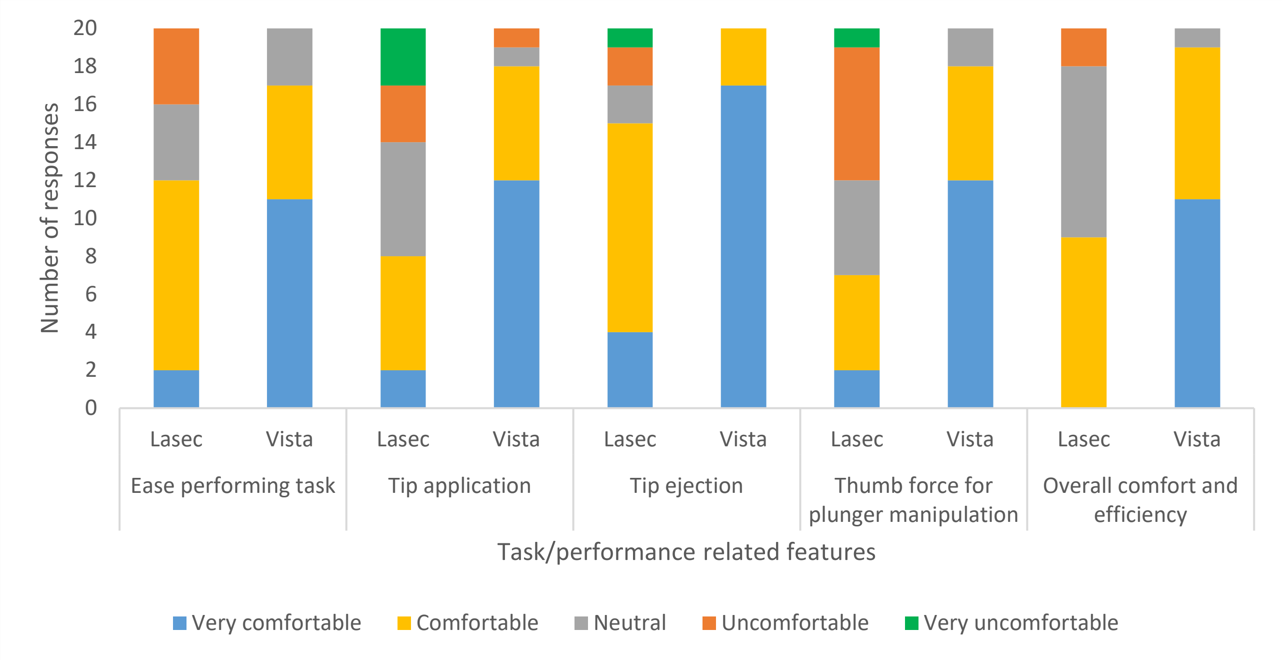

Figure 25: A comparison of the frequency of comfort responses for the task/performance-related features between a traditional pipette model (Lasec) and an ergonomically designed pipette model (Vista).

The Lasec model was found to have less comfortable task/performance-related features in comparison to the Vista model (see Figure 25, page 68). Ease of task performance, tip application, tip ejection, and thumb force for plunger manipulation of the traditional pipette model had more unfavourable comfort responses in comparison to the ergonomic pipette model. Thumb force for plunger manipulation of the Lasec pipette model was the least comfortable feature of the pipette model as 35% of the participants found it uncomfortable and 5% found it very uncomfortable. Tip ejection was found to be the most comfortable feature of the ergonomic pipette model, as 85% of participants reported it to be very comfortable and 15% found it to be comfortable (refer to Figure 25, page 68). Overall, users found the ergonomic pipette model more comfortable and efficient (55% found it very comfortable, and 40% found it comfortable) in comparison to the traditional pipette model.

Comfort responses between the two pipette models were paired and compared using the Wilcoxon matched pairs test (see Appendix S).

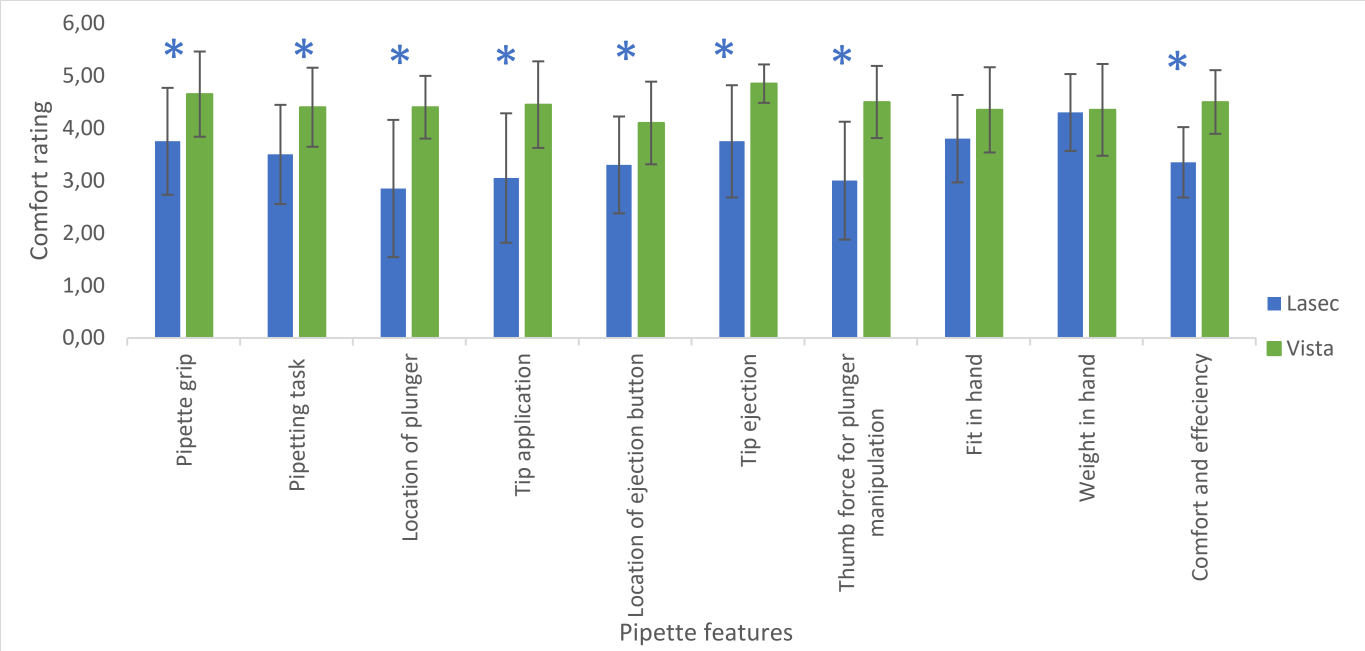

Figure 26: A comparison of the mean (and standard deviation) comfort responses between the features of a traditional pipette model (Lasec) and an ergonomic pipette model (Vista). (* denotes significant difference between models p<0.05).

Significant differences (p<0.05) were found in the comfort responses of the pipette grip, location of plunger, tip application mechanism, location of ejection button, tip ejection, thumb force for plunger operation, and overall comfort and efficiency between the traditional and the ergonomic pipette models (See Figure 26, page 69 and Appendix S). Users found that these features were much more comfortable on the ergonomic pipette in comparison to the traditional pipette. Tip ejection (4,85) and pipette grip (4,65) of the ergonomic pipette model were perceived to be the most comfortable features between the two pipette models. The location of the plunger (2,85), thumb force for plunger manipulation (3,00), and tip application (3,05) of the traditional pipette model were found to be the least comfortable features between the two pipette models. In addition, a large variation was found in the comfort responses of these pipette features for the Lasec pipette model (location of plunger 45,93%; thumb force for plunger manipulation 37,46%; and tip application 40,47%) (refer to Appendix T). The Vista model was perceived to be significantly more comfortable and efficient than the Lasec model (refer to Figure 26, page 69).

No significant differences were found in the comfort ratings of the weight of the pipette and fit in hand between the traditional and the ergonomic pipette model.

4.4.3 Preference

Participants were asked to report on their preferred pipette model and given the option to comment on the features and their experience of using each pipette model. This was done to assess each pipette model's usability and overall user perception.

Comments made on the pipette models were recorded and categorized. The categories included: Ease of use and preference, plunger comfort, ejection button, force for tip insertion, handle and shaft width, position, and size, finger-hook, task performance, and overall perception (see Appendix U).

It was found that 70% of the participants preferred the ergonomic pipette model, 15% preferred the traditional pipette model, and 15% chose not to say. Preference of the traditional pipette model was found to be influenced by familiarity.

Participants found the traditional pipette (Lasec) easier to use due to familiarity with the model and frequent use in laboratories. In addition, participants liked the width of the pipette as they felt it was accommodating to users with different hand sizes. However, features such as the long pipette plunger, ejection button, force for tip insertion, the length of the pipette body and shaft, and the stationary finger hook were found to be unfavourable and problematic for users. In terms of task performance, users found it hard to keep a uniform rhythm/ pace of work and found that it was easy to lose focus and make mistakes when using the Lasec model. In addition, some users found that it took longer to perform pipetting tasks using the Lasec model.

In contrast, participants found the ergonomic pipette model difficult to use due to unfamiliarity and reported that more time and practise was required to acquaint themselves with the pipette model and its functions. In addition, participants reported that the pipette model was somewhat heavy, too thick, not accommodative for different hand sizes, and strenuous to the wrist because of how it is held during operation (see Figure 16, page 53). It was noted that the major problem associated with the ergonomic pipette model was the size and width of the pipette model, which users felt affected the grip of the pipette and their ability to reach for pipette functions, such as the ejection button. Features of the Vista pipette model which participants liked included the adjustable finger hook, the audible click feedback when inserting a tip, the sideways orientation of the pipette shaft, and the short body of the pipette which made it easier to work closer to the workbench. For task performance, participants found that they could maintain focus and a consistent workflow/pace when using the ergonomic pipette model.

4.5 Correlations between anthropometric measures and dependent variables

To determine the relationship between the data, cross correlations were conducted between hand anthropometric data and biomechanical responses (Muscle activity), as well as between hand anthropometric data and subjective responses (RPE and comfort ratings). These were done to assess whether the different pipette models affected the relationship between hand sizes and muscle activity, as well as subjective responses.

4.5.1 Cross correlations between hand anthropometry variables

Hand anthropometric responses were correlated with hand anthropometric measures. All covariates correlated with each other (see Appendix V). This was expected as generally larger hands correspond with large hand, palm, and thumb dimensions, and smaller hands correspond with small hand, palm, and thumb dimensions. Hand, palm, and thumb dimensions included hand length, palm length, hand width, palm circumference, thumb length, and hand thickness. Correlation tables are shown in Appendix U.

4.5.2 Correlations between hand anthropometric measures and Ratings of perceived exertion (RPE) responses

Hand anthropometric measures were correlated with the Ratings of perceived exertion responses (at the level of the hand, thumb, wrist, and forearm) of the two pipette models. No correlations were found between perceived exertion and hand anthropometric measures. Correlation tables are shown in the Appendix W.

4.5.3 Correlations between hand anthropometric measures and Muscle activity responses

Correlations were made between hand anthropometric measures and muscle activity responses of OPP, APB; FPL; EPL; APL, EPB; and BRACH muscles for both pipette models. Moderate negative linear correlations ($-0{,}4 > r \geq -0{,}8$) were found between various muscles and anthropometric measures. The significant results are shown in Table 5 below. Detailed correlation tables and non-significant correlations are shown in Appendix X.

Table 5: Correlations between hand anthropometric measures and muscle activity responses of five different muscles for two pipette models. Only Significant r-values are displayed.

Variable	Correlations (Anthropometric data with muscle activity responses) Marked correlations are significant at p < .05000									
	Lasec OPP, APB	Lasec FPL	Lasec APL, EPB	Lasec EPL	Lasec BRACH	Vista OPP, APB	Vista FPL	Vista APL, EPB	Vista EPL	Vista BRACH
Hand Length	-0,45				-0,59					-0,60
Palm Length	-0,45									
Hand Width	-0,55									-0,47
Palm Circumference					-0,52	-0,18				-0,58
Thumb Length				-0,45	-0,51	-0,54		-0,51		-0,49
Hand Thickness					-0,67			-0,52	-0,50	-0,69

Significant differences were found between some hand anthropometric measures and muscle activity of various muscles between the two pipette models (Table 5, page 72). It was found that muscle activity increased for smaller hands, indicating that users with smaller hands exerted more force to operate the two pipette models (this is shown by the negative correlation coefficients). No significant differences were found between the FPL, APL, and EPB muscle activity responses for the Lasec pipette model and hand anthropometric measures, as well as between the FPL muscle activity responses of the Vista pipette model and hand anthropometric measures.

4.5.4 Correlations of Anthropometric data with Questionnaire (Comfort) responses of two different pipette models

To assess the effects of the different pipette models on the perceived comfort and usability of users with different hand sizes, hand anthropometry measures were correlated with comfort responses. The comfort responses included comfort and usability ratings of various pipette features in the form of a questionnaire. The questionnaire consisted of 10 questions where question 1- Comfort of pipette grip; question 2- ease and comfort in performing pipetting task using pipette; question 3- location of plunger; question 4- tip application, question 5- location of ejection button; question 6- tip ejection; question 7- thumb force for plunger manipulation; question 8- overall fit in hand; question 9- weight in hand; and question 10- overall comfort and efficiency. The detailed correlation table can be found in Appendix Y.

Table 6: Significant correlation coefficients (r-values) between hand anthropometric measures and questionnaire responses of two different pipette models (Lasec and Vista).

	Lasec		Vista	
Variable	Q1	Q3	Q5	Q9
Hand length		-0,59		
Palm length	-0,46	-0,57		
Hand width			-0,59	-0,48
Palm circumference			-0,49	
Hand thickness			-0,61	

Various hand anthropometric measures were found to correlate with comfort responses of various pipette features (see Table 6, page 73). Participants with small hands and small hand dimensions (hand length, palm length, hand width, palm circumference, and hand thickness) rated various features of each pipette model with high comfort ratings (shown by the negative r-values). This indicates that users with small hands found the pipette features more comfortable than users with larger hands. Features included Lasec's pipette grip and location of plunger, as well as Vista's ejection button and weight in hand. Detailed correlation tables are found in Appendix Y.

4.6 Summary of results

4.6.1 Biomechanical responses

Pipette design was found to have no significant effect on the muscular loading of the flexor pollicis longus (FPL), abductor pollicis longus (APL), extensor pollicis brevis (EPB), extensor pollicis longus (EPL), and brachioradialis (BRACH) muscles. The effect of pipette design was only significant ($p<0.05$) in the muscle activation of the abductor pollicis brevis (APB) and opponens pollicis (OPP) muscles. The ergonomically modified pipette model (Vista) resulted in a significant reduction in the muscular loading of the APB and OPP muscles. The flexor pollicis longus muscle was the most activated muscle for both pipette models in comparison to the other muscles. This finding indicates that the FPL muscle is more active during pipette operation and is exposed to increased muscular loading in comparison to the other muscle groups. The Vista model resulted in reduced FPL muscle activity in comparison to the Lasec model however, this finding was not significant. The APB, OPP, and FPL muscles are responsible or thumb movement, and thus play a pivotal role in plunger manipulation and tip ejection. A reduction in the muscular loading of these muscles associated with the Vista model indicate that the model required lower forces for plunger manipulation and tip ejection in comparison to the Lasec model, and thus reduced muscular strain of these muscles.

Pipette design was found to have no significant effect on wrist range of motion along the sagittal and frontal planes. When considering different wrist postures, the Vista model was found to significantly reduce radial deviation during pipetting in comparison to the Lasec model. However, it increased ulnar deviation and wrist flexion. In contrast, the Lasec model rendered lower ulnar deviation and wrist flexion. No significant difference was found in the wrist extension responses between the two pipette models. Thus, the ergonomic pipette model was found to be good at reducing radial deviation, however it exposed users to increased flexion and ulnar deviation.

4.6.2 Performance responses

Pipetting with both pipette models had no significant effect on the time taken to complete pipetting tasks. This highlights that an ergonomic incorporation to pipette design does not negatively impact performance, nor improve it.

4.6.3 Subjective responses

Performing pipetting tasks using the Vista model was perceived to require significantly lower muscular effort of the thumb, hand, wrist, and forearm in comparison to the Lasec model. The thumb was perceived to exert the most effort during pipetting using the two pipette models. This is because during pipetting, the thumb is primarily responsible for pipette operation in comparison to the other body regions. The Vista model was perceived to require lower thumb effort than the Lasec model.

In addition, the Vista pipette was the preferred pipette model which was perceived to have more comfortable design-related and task related features. The pipette features of the two pipette models had a significant effect on usability and comfort responses. The Vista model was perceived to have significantly more comfortable features, with pipette grip and tip ejection perceived to be the most comfortable features of the pipette model. The Lasec model was perceived to be less comfortable, and features such as thumb force for plunger manipulation, location of the plunger, and tip application were perceived to be the least comfortable features associated with the pipette model. Some participants preferred the Lasec model due to familiarity and frequent use.

4.7 Response to hypothesis

4.7.1 Null Hypothesis 1: Biomechanical responses

It was hypothesized that biomechanical responses including muscle activity, wrist posture, and range of motion would be the same between the traditional pipette model and the ergonomic pipette model.

Muscle activity

Muscle activation levels of the brachioradialis, abductor pollicis longus, extensor pollicis brevis, flexor pollicis longus, and extensor pollicis longus muscles between the two pipette models were not significant, thus the null hypothesis is accepted in this regard. However, a significant difference was found in the muscle activity of the opponens pollicis and abductor pollicis brevis muscles between the two pipette models. Therefore, the null hypothesis is rejected with regards to these muscles.

Wrist posture and Range of motion

Wrist posture with regards to radial deviation, ulnar deviation, and wrist flexion was significantly affected by pipette design. Therefore, the null hypothesis is rejected with regards these wrist postures. However, no significant difference was found in the wrist extension responses between the two pipette models, thus the null hypothesis is accepted for wrist extension. In addition, wrist range of motion along the sagittal plane and frontal plane was the same for the ergonomic and traditional pipette model; therefore, the null hypothesis is accepted for wrist ROM.

4.7.2 Hypothesis 2: Performance responses

It was proposed that performance would be the same between the traditional pipette model and the ergonomic pipette model.

There was no significant difference observed in the time taken to complete pipetting tasks between the traditional pipette model and the ergonomic pipette model. The null hypothesis is therefore accepted.

4.7.3 Hypothesis 3: Subjective responses

Subjective responses on perceived comfort and exertion were proposed to be the same between the traditional pipette model and the ergonomic pipette model.

Ratings of perceived exertion

Ratings of perceived exertion at the level of the hand, thumb, wrist, and forearm, varied significantly between the two pipette models. Thus, the null hypothesis is rejected.

Comfort and usability

No significant difference was found in the comfort and usability ratings of the weight-in-hand and fit-in-hand between the two pipette models; thus, the null hypothesis is accepted for these features. The comfort and usability ratings of the other pipette features varied significantly between the pipette models; thus, the null hypothesis is rejected in this regard. Features with statistical significance included pipette grip, ease to perform pipetting task, location of plunger, tip application, location of ejection button, tip ejection, thumb force for plunger manipulation, and overall comfort and efficiency.

Chapter 5

Discussion

Introduction

Manual repetitive pipetting has been associated with various risk factors such as high forces, high repetition, and awkward postures which place pipette operators at a risk of developing musculoskeletal disorders (Unyi & Asato, 2015). The design of manual pipettes and their features have been associated with various repetitive strain injuries and contribute significantly to the MSD risk associated with pipetting (Sormunen & Nevala, (2013); ARTEL, n.d.). Various manufacturers have recognized this risk and have attempted to redesign traditional pipettes. Furthermore, several authors suggest the implementation of ergonomics to pipette design to reduce the MSD risk associated with manual pipetting (Lu et al., 2008; Kim et al., 2020). Thus, this current study set out to assess the effects of an ergonomically modified mechanical pipette model on biomechanical, subjective, and performance measures, and to compare the responses to those of a traditional pipette model. This is because the application of ergonomics to tool design can help reduce physical risk factors attributed to pipette design while improving performance and user wellbeing. Thus, the results presented in the previous chapter and the discussion presented here forth refer to the use of an ergonomically modified pipette model to address the physical risk factors attributed to pipette design.

5.1 Biomechanical responses

5.1.1 Muscle activity

Pipette model was found to significantly affect the muscular loading of the abductor pollicis brevis (APB) and opponens pollicis (OPP) muscles. The ergonomic pipette model (Vista) rendered significantly lower muscular loading of the (APB) and (OPP) muscles in comparison to the traditional pipette model (Lasec). The APB and OPP muscles are thenar eminence muscles that move the thumb and are integral in operating the pipette plunger and ejection button during pipetting (Selvaraj, 2014). Furthermore, during pipetting, thumb muscles work as mobilizers and stabilisers consecutively and dynamically to operate pipette functions and to grip the pipette, and the muscular loading of these muscles is influenced by the diameter of the pipette and the length of the plunger (Fredriksson, 1995; Wu et al., 2014). Given that the length of the pipette plunger influences the force produced and muscle activity of the thumb muscles, the observed reduction in muscle activity of the APB, and OPP muscles for the Vista model can be attributed to the short plunger of the Vista pipette which resulted in reduced thumb abduction, and the reduced plunger operational forces reported by the pipette manufacturer (VistaLab Technologies, 2001). In addition, the inverse relationship observed between hand anthropometric measures and muscle activity (see Table 5, page 72), whereby users with small hand dimensions had increased muscle activity during the operation of the two pipette models, can be attributed to pipette diameter. This finding indicates that users with small hands required more muscular force to grip and operate the two pipette models, revealing that the grip diameter of these pipettes does not accommodate users with small hand dimensions and can result in muscular strain. Furthermore, increased grip diameter (greater than 5cm) has been associated with reduced grip strength and high grip forces (Lee & Jiang, 1999; Edgren et al., 2004; Lu et al., 2008). Given that both pipette models have diameters exceeding 5 cm (Lasec= 10,4 cm and Vista = 12,6 cm), they expose users to increased hand strain.

Although a significant difference was found in the muscle activity of the APB and OPP muscles for the two pipette models, the flexor pollicis longus muscle (FPL) rendered the highest muscle activation levels for both pipette models (28,40 ± 12,99% Lasec and 25,48 ± 12,00% Vista) in comparison to the other muscles. This finding corresponds to Lintula & Nevala (2006) and Kim et al. (2020) and can be attributed to users excessively flexing their thumb at the interphalangeal joint or applying excessive thumb force to operate pipette features. The FPL muscle is responsible for thumb flexion at the interphalangeal joint, which is the movement required to press pipette controls (Wu et al., 2014). Contrary to this finding, Wu, and colleagues (2014) found that pipetting with traditional manual pipettes resulted in increased activity and forceful loading of the abductor pollicis brevis (APB) and flexor pollicis brevis (FPB) muscles, with the APB muscle exerting maximal force during pipetting. In addition, a study using ultrasound imaging to quantify thumb force and muscle activity of the thenar eminence muscles (APB, OPP, and FPB) during pipetting, found that pipetting resulted in increased force output of all the thenar eminence muscles, with greater muscular activation of the APB and FPB muscles (Selvaraj, 2014). Wu and colleagues (2014) and Selvaraj (2014) explain that increased muscular loading of the APB, and FPB muscles during pipetting is attributed to the thumb movements and force generated during the operation of pipette features. Selvaraj (2014) explains that the APB muscle functions to abduct the thumb, whilst the FPB flexes the thumb, indicating that thumb motion during pipetting mainly comprises of thumb abduction and flexion. The discrepancy between the results of this study and those of Wu and colleagues (2014) and Selvaraj (2014), can be attributed to the different methods used to analyse muscle activity (Wu et al. (2014) used an inverse dynamic model, whereas Selvaraj (2014) used ultrasound imaging)). Other explanations include the manual data processing used in this study, as well as the grouping of the APB and OPP muscles as a "single muscle" due to their proximity and similar action lines, so the activity presented in this study was the sum of the two muscles' activity. In addition, FPB muscle activity was not measured in this study due to its proximity to the APB and OPP muscles and the placement of an electrode over this muscle, which would result in signal interference. Muscle activity results may have also been influenced by the fact that EMG is subject to a large variation (Cram & Kasman, 2014), and muscle fatigue arising from the repetitive loading of the muscles for an extended period which resulted in the recruitment of more motor units.

The Vista model required lower muscular effort of the FPL muscle compared to the Lasec model; however, this difference was not significant. The muscular loading of the FPL muscle was expected to be lower for the Vista model in comparison to the Lasec model due to the reduced plunger pressure and plunger height of the Vista pipette, which would elicit less thumb flexion and abduction. The reduction in FPL muscle activity for the Vista pipette would also result from the reduced tip ejection force and the location of the tip ejection button, which places the thumb in a neutral position. Furthermore, manufacturers claim that the Vista model reduces flexor muscle activity (4,8% MVC) compared to other traditional pipette models (VistaLab Technologies, 2001), however, the results of this study do not support this statistically. The lack of significance in FPL muscle activity between the two pipette models could be attributed to the sample size (a larger sample might produce significant results), and muscle activity variation attributed to the manual processing of the EMG data.

The flexor muscle activity reported by manufacturers is lower than that observed in this study. This could be because VistaLab Technologies (2001) did not specify which flexor muscles were tested, resulting in the discrepancy. Furthermore, the manufacturers also reported on muscle activity during a single pipette action (dispensation), whereas the muscle activity in this study was that of 40 pipette cycles. In addition, Lintula & Nevala (2006) reported that the muscular strain of the FPL muscle was lower for the shortest and lightest pipette and linked to the light dispensation button and reduced abduction of the thumb resulting from the pipette. In the current study, the Vista model was the shortest pipette between the two models (Vista 15,5 cm and Lasec 28,2 cm), with a light dispensation button; however, it was also the heaviest model (Lasec 98g and Vista 140g). The weight, length, and circumference of pipettes have been reported to contribute to the muscular loading of the shoulder, wrist, arm, hand, and forearm muscles (Lintula & Nevala, 2006; Sormunen & Nevala, 2013). Therefore, although the Vista model might reduce FPL activity, its heavy weight could increase the muscular loading of other muscles.

No significant differences were found in the muscular loading of the flexor pollicis longus, extensor pollicis longus, extensor pollicis brevis, abductor pollicis longus, and brachioradialis muscles between the Lasec and Vista pipette models. This could be because the traditional pipette model used in this study had modifications (such as reduced plunger and ejection forces) which reduced physical requirements for operation; thus, the muscular load placed on the abovementioned muscles was similar for both pipette models. In addition, it was observed that the APL; EPB, and EPL muscles had relatively high muscle activity levels (21,80% Lasec, 21, 83% Vista; and 25,65% Lasec and 23,26% Vista respectively) in comparison to the APB, and OPP muscles. This could be explained by findings by Asundi and colleagues (2005) that pipetting requires controlled thumb motion which is facilitated by the static loading of EPB, APL and FPL, as well as the APB muscles. Asundi et al. (2005), explain that the EPB and APL muscles act as metacarpal and carpometacarpal joint stabilizers, whilst APB and FPL function to operate the pipette plunger. It was thus assumed that the APL, EPB, EPL, and brachioradialis muscles were responsible for joint stabilization during the performance of pipetting tasks using both the pipette models. Furthermore, Wu et al. (2014) and Selvaraj (2014), explain that the OPP is responsible for thumb opposition (movement at the carpometacarpal joint); therefore, this muscle contributes less to pipetting and only plays a role in maintaining carpometacarpal joint stability during pipetting. This observation cannot be directly linked to the results of this study as the muscle activity of the OPP was recorded together with that of APB. The Brachioradialis (BRACH) muscle was the least activated muscle for both pipette models (3,45% for Lasec and 3,38% for Vista); this is because during pipetting, Brachioradialis does not actively play a role in pipette operation, but rather acts as a forearm stabiliser and maintains arm flexion.

The muscle activity levels of the APB, OPP, FPL, APL, EPB, and Brachioradialis muscles during the operation of the two pipette models were compared to recommended safety limits of muscular loading. Given that pipetting comprises static and dynamic muscular loading, static and dynamic force recommendations were compared to the results of this study. The recommended dynamic force threshold for repetitive or sustained exertion is 20%-30% of maximum strength capacity (Rainin, 2016), whereas the recommended endurance limit for static contractions produced for 10 minutes is 15% of MVC, and 8% of MVC over 60 minutes (Bjorksten & Jonsson, 1977). Bjorksten & Jonsson (1977) also mention that when muscular contractions are repeated continuously (for instance over an 8-hour shift), without sufficient rest, the endurance limit is below 8% of MVC. Forces exceeding these recommended thresholds can lead to muscle fatigue, injury, and MSD development. When comparing the results of this study to the recommended thresholds, it is evident that pipetting with both the pipette models investigated in the current study exposes muscles, except for brachioradialis, to high static and dynamic muscular loading. The dynamic muscular loading for both pipette models is reasonable (falls within thresholds), however, both pipettes expose users to excessive static loading which exceed guidelines and may cause injury. The Vista model was found to reduce dynamic loading of the APB and OPP muscles to an acceptable level and static loading of these muscles falls within the threshold of static loading. These findings correspond with other studies that assessed muscle activity and force during pipetting and found that pipette operating forces exceed maximum thumb push force capacities, and recommended peak and maximum dynamic and static force capacities for men and women (Fredriksson, 1995; Erickson & Woodard, 2001; Asundi et al., 2005; Burt et al., 2016; Rainin, 2016). Although these studies reported on hand and thumb forces in relation to muscle activity during pipetting, the present study did not measure force; however, given that the amount of force produced by a muscle is dependent on motor unit activation patterns and properties of muscle fibres (Cao et al., 2017), it can be assumed that high levels of muscle activation are indicative of increased force production. Thus, when considering the force as a percentage of maximal contraction exerted during pipetting over an 8-hour work shift, it becomes apparent that pipetting with both pipette models poses a high risk of muscular strain and injury especially to the FPL, APL, EPB, and EPL muscles. Prolonged exposure of the above-mentioned muscles to pipetting can result in repetitive strain injuries such as tenosynovitis and increase MSD risk (Asundi et al., 2005; Wu et al., 2014).

In summary, the Vista model resulted in a reduction in muscle activity (especially of the APB and OPP muscles) and a reduction in the dynamic muscular loading of the APB, and OPP muscles; however, the static muscular loading of muscles (except for brachioradialis and APB, OPP) during the operation of the Vista model was still high and exceeded recommended levels. This highlights that the design of the ergonomic model still exposes pipette operators to high levels of static muscular loading and poses a risk for MSD development, thus, pipette operational forces must still be reduced, and pipettes redesigned to reduce muscular strain associated with pipetting.

5.1.2 Wrist movement responses

Wrist range of motion

The results revealed that pipette design had no significant effect on wrist range of motion. No significant differences were found in sagittal and frontal plane wrist ROM between the two pipette models. Although statistical significance between the different planes was not measured, it was found that pipetting with both models resulted in increased wrist frontal plane range of motion in comparison to sagittal plane motion. This is because during pipetting, the wrist is frequently bent (ulnar and radial deviation) along the frontal plane when pipette operators pick up the pipette, insert a tip, aspirate fluid, locate the dispensation container, dispense fluid, locate the disposable tip bucket, and eject a tip. In addition, the placement of the apparatus and the height of the sample container and tip disposable bucket could have contributed to the increase in frontal plane motion.

Wrist posture

Pipette design significantly affected radial deviation, ulnar deviation, and wrist flexion ($p<0.05$) during pipetting. No significant difference was, however, found between the Vista and Lasec wrist extension responses. Although the Vista resulted in less wrist extension in comparison to the Lasec, the reduction was not significant. Wrist extension responses may render statistical significance with an increase in sample size. The postural joint angles of this study were comparable to those reported by Lee & Jiang, (1999); Lu et al. (2008); and Kim et al. (2020) in similar studies (Table 7, page 85). The ulnar deviation of the Vista model was slightly higher (by 3°) than the ulnar deviation angles reported by Lu et al. (2008). These differences can be attributed to the different conditions assessed by Lu and colleagues (2008), whereby wrist posture was measured during pipetting while participants were seated and standing, whereas the joint postures reported in this study are based on pipetting while standing. In addition, the joint ranges reported by Lee & Jiang (1999) were higher because they investigated snapshots of joint postures assumed during different pipetting actions (tip insertion, vessel loading, mixing, and gel loading), which involved sustained static postures. In this study, wrist joint postures were measured for the overall 40 pipette cycles for each pipette model.

Pipetting with the Vista model significantly reduced joint angles for radial deviation in comparison to the traditional pipette model. The reduction in radial deviation associated with the Vista model is attributed to the short length of the pipette and the non-axial grip which resulted in users pipetting closer to the midline of the body and maintaining more neutral wrist positions. Although the Vista model reduced radial deviation during pipetting, it resulted in a significant increase ($p<0.05$) in ulnar deviation and wrist flexion in comparison to the Lasec model. The increase in ulnar deviation and wrist flexion associated with the Vista model could be attributed to the placement of pipetting equipment, as well as the height of the sample container and disposable tip bucket relative to the short pipette length which resulted in participants excessively bending their wrist (towards the ulna) to aspirate fluid and eject tips. In addition, users' unfamiliarity with the Vista model could have resulted in the excessive radial deviation and flexion. Furthermore, the way the Vista model is gripped during operation (which results in a horizontal orientation of the hand, as shown in Figure 16, page 53) could be the reason for the increased ulnar deviation.

Table 7: A comparison of wrist joint angles between this study and those reported by various authors. Wrist movements included radial deviation, ulnar deviation, wrist flexion, and extension.

Wrist position	**This study**	**VistaLab Technologies (2001)**	**Lintula & Nevala (2006)**	**Lu et al. (2008)**	**Kim et al., (2020)**	**Lee & Jiang (1999)**
Radial deviation	Lasec: 14,04 ± 8,42° Vista: 5,22 ± 18,82°	Traditional pipettes: 20-21,8° VistaLab: 9,7°			1-27°	8,6-31,1°
Ulnar deviation	Lasec:16,72 ± 11,61° Vista: 25,57 ± 15,37°	Traditional pipettes: 3,5-4,5° Vista: 5,8°	Long pipette models (10-13°) Shortest pipette (6°)	12-22° All pipetting actions	2-26°	
Flexion	Lasec: 16,63 ± 21,74° Vista: 31,60 ± 21,35°	Vista: 7,1°entire cycle 6,7-21,9° individual pipetting actions			5-37°	23,2-45°
Extension	Lasec: 27,67 ± 16,58° Vista: 15,39 ± 23,51°	Vista: 6,2° entire cycle 2,8-7,9° individual pipetting actions	20-27° All pipette models	23-41°	1-38°	

Contrary to the abovementioned findings, Lu and colleagues (2008) found that pipetting with the Vista pipette resulted in a 20-30% decrease in ulnar deviation when compared to traditional axial pipettes. Discrepancies were also found between the results of this current study and the reported postural observations made by the manufacturer (VistaLab Technologies, 2001) (see Table 7, page 85). Furthermore, Lintula & Nevala (2006) reported that shorter and lighter pipettes resulted in reduced ulnar deviation. The Vista model was the shortest and heaviest model in this study, and thus the weight of the pipette could have contributed to the increase in ulnar deviation and wrist flexion as users adopted awkward wrist postures to balance and stabilise the pipette in the hand during pipetting tasks. The discrepancies found between the results of this study and those of (VistaLab Technologies, 2001; Lintula and Nevala, 2006; and Lu and colleagues 2008), can be attributed to measurement errors made during the experiment whereby the goniometer was not calibrated properly, and the placement of the pipetting apparatus was not uniform and was moved by the user to their preference. A variation was also observed in how participants held the pipettes during pipetting tasks, and given that participants determined their own pipetting postures, these factors could have also contributed to the postural variability and impacted the joint angles recorded. Furthermore, given that goniometry is subject to cross talk and zero-drift (Foltran et al., 2013; Hughes & Babski-Reeves, 2016) this could've influenced results as a large variation was found between individual wrist responses. Lastly, the studies by VistaLab Technologies (2001), and Lu and colleagues (2008) assessed wrist postures during individual pipetting tasks, whereas this study assessed overall wrist postures over 40 pipette cycles.

To assess the risk and strain placed on the wrist during the operation of the Vista and Lasec pipette models, wrist postural responses of this study were compared to recommended wrist safety levels. The wrist responses were compared to Pheasant & Haslegrave's (2018) Body space tables for wrist joint range of motions for the 5^{th}, 50^{th}, and 95^{th} percentiles (refer to Table 8, page 87).

Table 8: A comparison of wrist postural ranges of motion between the joint postural responses of this study and Pheasant & Haslegrave (2018) body space tables for wrist joint range of motion for the 5th,50th, and 95th percentiles. Joint positions included radial deviation, ulnar deviation, wrist extension, and wrist flexion.

	Wrist position observed in this study		Wrist joint range of motion according to Pheasant & Haslegrave (2018)			
Joint position	Lasec	Vista	5th percentile	50th percentile	95th percentile	SD
Radial deviation	14,04° ± 8,42	5,22° ± 18,82	12°	27°	42°	9
Ulnar deviation	16,72°± 11,61	25,57° ± 15,37	35°	47°	59°	7
Wrist Extension	27,67° ± 16,58	15,39° ± 23,51	78°	99°	120°	13
Wrist Flexion	16,63 ± 21,74	31,60 ± 21,35	70	90	110	12

As presented in Table 8, all wrist joint postures for both pipette models were found to fall below Pheasant and Haslegrave's (2018) 5th percentile ranges for wrist range of motion. This indicates that both pipette models resulted in relatively low wrist ranges of motion which accommodate users within the 5th percentile (i.e., individuals with small wrist range of motion). The traditional pipette model (Lasec) was found to result in radial deviation approximately 2-3 degrees higher than Pheasants' 5th percentile value. This, however, is still within an acceptable range, as the radial deviation falls within the 5th-50th percentile range of motion. The joint ranges of motion proposed by

Pheasant & Haslegrave (2018) are limited by the fact that they are based on European male joint ranges of motion. However, because females are reported to have greater flexibility than men (5-15° more) (Pheasant & Haslegrave, 2018), the proposed joint ranges might still be applicable to the results of this study and show that both pipette models result in ranges of motion that accommodate male and female users within the 5^{th} percentiles. Furthermore, while the anthropometric data reported by Pheasant & Haselgrave (2018) is not ideal (as it's based on a European population), it was the best and only available data to compare the findings of this study to.

The wrist joint angles of the different pipette models were also compared to Keir et al., (2007) and Ketola et al. (2010) who recommended wrist posture safety margins. Non-neutral wrist postures were classified as wrist flexion, extension, radial deviation, and ulnar deviation beyond 20 degrees (Ketola et al., 2010). Keir and colleagues (2007) reported wrist posture threshold limits based on carpal tunnel pressure and defined safe or neutral wrist angles as angles that did not exceed 26,6° wrist extension, 37,7° flexion, 12,1° ulnar deviation, and 17,8° radial deviation. Wrist joint angles exceeding these recommended thresholds have been associated with increased risk of repetitive strain injuries such as carpal tunnel syndrome, and upper limb MSDs. Based on these studies, the traditional pipette model resulted in neutral wrist postures, except for wrist extension (27,67°) and ulnar deviation (16,72°) (based on Keir and colleagues, 2007 threshold limit). In contrast, the ergonomic pipette model resulted in non-neutral ulnar deviation (25,57°) and wrist flexion (31,60°) which exceeded recommended safety thresholds.

Non-neutral wrist postures have been associated with a high risk of hand and wrist injuries, tendon-related disorders, and carpal tunnel syndrome (Keir et al., 2007). In addition, Werner et al., (1997) and Barr & Barbe (2002) explained that tasks that involve movements of extreme wrist flexion and extension increase pressure in the carpal tunnel and contribute to the compressive loading of the median nerve more than radial and ulnar deviations. Furthermore, Fredriksson (1995) mentioned that during pipetting the wrist is extended to a 30° static position, which overtime may lead to injuries and MSDs affecting the wrist. Thus, given that the Vista model resulted in a reduction in wrist extension (although it was not significant) it may reduce the strain placed on the wrist during pipetting. However, because of the increase in wrist flexion and ulnar deviation, it still poses a risk for carpal tunnel syndrome and upper limb ailments on users. It is therefore recommended that pipette manufacturers and operators minimize wrist flexion and extension to avoid upper limb injuries and ailments. Sormunen & Nevala (2013) suggested that manufacturers of hand tools consider anatomical and physiological factors present during work.

Overall, the biomechanical responses highlight that the ergonomic pipette model is good at reducing muscular loading of the APB and OPP muscles and reducing radial deviation during pipetting. However, the pipette model still exposes users to high muscular loading and awkward wrist postures which exceed recommended safety levels. Thus, it is inconclusive whether the ergonomic pipette model is better than the traditional pipette model in terms of biomechanical factors.

5.2 Performance responses

Performance time was similar for both pipette models. No significant difference was found in the time taken to complete pipetting tasks between the two pipette models. This finding is in accordance with Lu and colleagues (2008), who found that time taken to complete pipetting tasks was similar between axial and non-axial pipettes; however, they reported that completing a pipette cycle with axial pipettes took 9,1 to 9,8 seconds whereas pipetting with the non-axial pipette took 8,8 seconds. The time taken to complete pipetting tasks reported by Lu and colleagues (2008) differed from the time observed in this study because Lu et al. (2008) investigated one pipette cycle, whereas 40 pipette cycles were investigated in the current study. Contrary to the present study's findings, Lichty et al. (2011) evaluated the ergonomics and usability of ten single-channel pipettes and found that the Vista pipette model took the longest time to complete the pipetting task compared to other pipette models. The differences in results can be attributed to the fact that the task analysed by Lichty and colleagues (2010) involved users aspirating samples from a microcentrifuge tube into 8 wells of a 96 well plate, and users had to continuously adjust the volume to be aspirated in between the pipetting tasks, whereas in the current study the volume was fixed and the task was less complex, meaning less time was taken. Furthermore, the accuracy of task performance was not measured in this study, and this could have influenced the time taken to complete pipetting tasks as less accurately sampled volumes could be attributed to quicker times as participants self-paced. In addition, Lichty et al. (2011)

reported that the Vista pipette took more time due to users' unfamiliarity with the model. This was however not the case in this study as, despite users' unfamiliarity with the model, their performance time was similar to the time taken with the traditional pipette model. This observation might possibly be attributed to the learning effect, as users performed the pipette cycle 40 times with the pipette model, which gave them an opportunity to adjust to using the pipette model. The effect of unfamiliarity with the model was also noted in the number of errors made with the Vista model in comparison to the traditional model, whereby users would often eject the tip in the Eppendorf tube when trying to aspirate or dispense a sample. This, however, was not the focus of this study, but can be investigated in future studies.

The average time taken to complete pipetting tasks in situ is approximately 5 minutes. However, because pipetting is a dynamic task that is often interrupted by additional tasks such as the opening and closing of vials/Eppendrof tubes, this time can vary considerably (Lintula & Nevala 2006). The time taken to complete pipetting tasks observed in the current study was between 7 to 8 minutes for both pipette models, however it was influenced by the opening and closing of Eppendorf tubes during pipetting tasks. It was noted that some users struggled with closing the Eppendorf tubes, and this increased the cycle time. In addition, given that participants were aware of the stopwatch, this might've influenced their performance.

The average time taken to complete pipetting tasks, and the number of times pipette operators perform pipetting tasks in an 8-hour shift highlight the repetitiveness of the task and the risk of injury associated with manual pipetting. Several epidemiological studies reported a dose-dependent relationship between pipetting and hand and shoulder ailments (Björksten et al., 1994; David & Buckle, 1997). Pipetting for 1 hour or more was associated with increased hand complaints (David & Buckle, 1997), whereas eight hours of pipetting a day was associated with increased hand, arm, and shoulder ailments (Bjorksten, 1994).

The findings on performance time indicate that the incorporation of ergonomics to pipette design does not hinder performance, but can help in reducing physical risk factors, as the ergonomic pipette model in this study was found to reduce various physical risk factors attributed to manual pipetting, without altering performance. This indicates a step towards reducing the MSD risk associated with manual pipetting, as the purpose of ergonomics is to match user capabilities to work tasks, and to improve user wellbeing and performance, while minimising exposure and risk of injury (Pheasant & Haslegrave, 2018; Rainin, 2016). In addition, although the redesign of pipettes cannot reduce the repetitive nature of pipetting, a reduction in the force and awkward postures can help minimise the risk of injury and MSD development.

5.3 Subjective responses

5.3.1 Perceived muscular exertion

Significant differences were found in the RPE ratings of the hand, thumb, wrist, and forearm between the two pipette models. The Vista model was perceived to require significantly lower muscular effort of the hand, wrist, thumb, and forearm compared to the traditional pipette model. This finding is comparable to similar studies conducted by Lintula and Nevala (2006) and Sormunen & Nevala (2013) who found that the shortest and lightest pipettes were perceived to place lower muscular strain on the upper extremities in comparison to longer pipettes. Although in this study the Vista model was the heaviest pipette, it resulted in lower perceived exertion at the body regions under investigation due to the reduced plunger force and short plunger height. In addition, the short body of the pipette allowed for a better grip and reduced hand forces, the audible click feedback reduced the force for tip insertion, and the non-axial grip placed the wrist in a more neutral position. Overall, the results of this study indicate that RPE ratings of the Vista model ranged from 8 to 9,5 which represented very light to light effort on the Borg RPE scale.

Participant perceptions revealed that the thumb exerted the most amount of effort for both pipette models. This can be attributed to the fact that the thumb is primarily responsible for pipette operations and therefore takes more strain in comparison to the other body regions. This observation can also be linked to the muscular loading of the FPL, APB and OPP muscles, as these are muscles responsible for thumb movement during pipetting. The link between RPE and muscle activity is corroborated by Steele et al. (2017) who explain that a relationship exists between load, perceived exertion, and physiological measures such as electromyography. Thus, given that the Vista model has a short plunger height, and reduced plunger operational forces, it required less muscular exertion of the APB, OPP muscles (shown in Figure 20, page 61) and required reduced thumb effort in comparison to the Lasec model.

Conversely, a study comparing the biomechanical responses and subjective discomfort between a traditional thumb push pipette and two ergonomic four finger push pipettes, found that the traditional pipette model was associated with increased discomfort in the hand, whereas the ergonomic models were associated with discomfort in the forearm (Kim et al., 2020). In this present study, the forearm was perceived to require the least amount of effort when operating the ergonomic pipette model. The results of this study differ from those reported by Kim and colleagues (2020) because of the different methods used to assess subjective responses. Kim et al. (2020) measured discomfort using a Borg CR-10 scale, whereas this study measured perceived exertion using a RPE scale. Furthermore, the pipette models used in the current study differed to those in the study by Kim et al. (2020) and thus placed strain on different regions. Despite the discrepancies mentioned, the ergonomic pipette model in this present study resulted in reduced perceived muscular strain and exertion.

It has been reported that in laboratory studies, measures of perceived physical exertion are indicative of the direct relationship between the physical demands of a task and the physical capacity of the worker (Williams, 2017). Thus, the low RPE ratings associated with the Vista model highlight the reduced effort during the operation of the ergonomic pipette model and in turn the low strain placed on users relative to their capabilities. This finding indicates that the use of the Vista model can reduce the perceived strain and exertion during pipetting, and in turn prevent muscular fatigue during pipetting. Additionally, given that the measured body sites are commonly affected regions during pipetting, the reduction of strain placed on these body parts, as a result of the ergonomic model, could reduce the incidence of upper limb MSDs and RSI's affecting these regions.

5.3.2 Comfort and usability responses

Comfort and usability results reveal that the Vista model was found to be associated with significantly better usability features in comparison to the Lasec model. Majority of the participants found the design-related and task/performance-related features of the ergonomic pipette model more comfortable than the traditional model's features.

The Lasec model was perceived to have the least comfortable features, with the location of the plunger, thumb force for plunger manipulation, and tip application being the least comfortable features of the pipette model. This is because the Lasec pipette model has a long plunger which requires excessive thumb extension and excessive thumb force to operate. Furthermore, because the pipette does not have a feedback mechanism indicating when a tip is inserted, it requires excessive force when inserting a tip as users often forcefully rock or twist the pipette to secure the tip. Various studies report that the force for tip insertion, when using traditional axial pipettes, often exceeds recommended safety thresholds (Erickson & Woodard, 2001; Rainin, 2016). This finding is in accordance with David & Buckle (1997) who reported on the ergonomic issues associated with traditional thumb push pipette models, and found that tip ejection and plunger manipulation were perceived as problematic features which made pipette operation difficult. Although tip ejection was not the least comfortable feature in this present study, it (tip ejection) has been associated with tip insertion forces, as increased tip insertion forces result in increased tip ejection forces in traditional axial pipettes (Rainin, 2016). Despite users finding the features of the Lasec model uncomfortable, many of the users (15%) preferred this model due to familiarity and its frequent use in laboratories. In addition, users commented on the width of the pipette model, which they felt accommodated different hand sizes in comparison to the Vista model.

In contrast, the Vista model was the preferred pipette (70% participants preferred it) with better usability and comfortable features. Tip ejection and pipette grip were found to be the most comfortable features of the ergonomic pipette model. This is because the tip ejection button of the pipette required very little thumb force for operation. In addition, the pipette model's non-axial grip and the adjustable finger-hook allowed users to operate the pipette with neutral hand positions, while the finger-hook also helped provide stability and grip in the preferred position. However, due to the thick handle of the pipette model, some users found the placement of the ejection button awkward and difficult to reach, resulting in the over-extension of the thumb. This is also shown by the high perceived exertion of the thumb associated with the Vista model.

Other features of the Vista model which participants found comfortable included the adjustable finger-hook, the audible click feedback mechanism when inserting a tip (as it reduced the amount of force required to insert a tip), and the sideways orientation of the pipette shaft which enabled users to work closer to the workbench without having to elevate the shoulder (reduced static loading of muscles). Some participants however, felt that the Vista model was difficult to operate due to unfamiliarity with the pipette. This was observed in the number of errors made while participants performed pipetting tasks using the Vista model. In addition, the Vista pipette model was perceived to strain the wrist due to the manner that it is held and operated during pipetting (the hand wraps the top of the pipette and assumes a horizontal orientation). The high ulnar deviation and wrist flexion associated with the Vista pipette model supports this finding.

No significant differences were found in the comfort responses to the fit-in-hand and weight-in-hand questions between the two pipette models. This could be attributed to the fact that participants found the length of the Lasec shaft too long which resulted in increased shoulder abduction and static loading of shoulder muscles, as well as the fixed finger-hook which restricted the users' flexibility to grip the pipette model and thus contributed to the discomfort. Furthermore, the axial grip of the Lasec pipette model has been associated with upper limb discomfort and various MSD risks (VistaLab Technologies, 2001; Costello at al. 2005; and Sormunen & Nevala, 2005). The Vista model was also found to be somewhat heavy, and too thick, which made it difficult to hold comfortably. This is because the Vista model was much heavier than the Lasec model, and increased pipette weight has been associated with poor balance and increased discomfort (Lichty et al., 2011). Users also reported that the thick handle of the Vista did not accommodate users with small hands. This finding is corroborated by the hand anthropometry and muscle activity correlations whereby users with small hands had to exert higher muscle contractions to grip the pipette, which increase muscular strain and fatigue. Contrary to this finding, correlations between hand anthropometry and comfort responses indicate that users with smaller hand dimensions rated various features of pipette models with high comfort ratings. The Vista model's ejection button and weight-in-hand were found to be more comfortable by users with small hand width, palm circumference, and hand thickness. This was an unexpected finding as it was anticipated that the larger pipette circumference would make it more difficult for users with smaller hands.

The subjective responses obtained in the current study are comparable to other usability and ergonomic evaluation studies investigating pipette design. These studies found that shorter and lighter pipettes with adjustable finger hooks, reduced operational forces, and smaller grip circumferences were associated with better comfort and usability ratings, as well as reduced biomechanical loading (Lee & Jiang, 1999; Lintula & Nevala, 2006; Erickson & Smith 2007; Lichty et al., 2010; Sormunen & Nevala, 2013). The difference between the results of this study and findings reported by the above-mentioned authors is that heavier pipette models with large grip circumferences were reported to be associated with increased perceived muscular strain, discomfort, and lower usability ratings. The Vista model in this study was the shortest and heavier pipette model of the two models investigated, with a larger grip circumference, yet it received better comfort and usability ratings and was perceived to require lower muscular exertion in comparison to the lighter pipette model (Lasec). This finding highlights the importance of designing hand tools relative to users' capabilities, because despite being perceived as more comfortable, the weight and grip diameter of the Vista model can be strenuous for users with smaller hands. The results might also be subject to bias due to the biased nature of subjective measures (David, 2005).

5.4 Integration of objective, performance, and subjective responses

Overall, the findings of this study highlight the impact that an ergonomic modification to pipette design has on biophysical, subjective, and performance aspects of pipette users. Although the objective results were inconclusive, with only some muscles showing reduced activity and some wrist postural angles reduced, the subjective results of this study indicate that users were in favour of the ergonomic model in comparison to the traditional model. Users preferred the Vista model particularly when it came to aspects of perceived muscular exertion, comfort, and usability features. Furthermore, subjective measures provide information on the perceptual aspects between the demands of a tool and user capabilities, and the degree of strain placed on users (Krawczyk, 2012). For instance, perceived exertion provides information on muscular strain, discomfort, and fatigue resulting from a work task or tool (Jakobsen et al., 2014). Thus, users' perceptions of the ergonomic model requiring less muscular effort and being more comfortable can be translated into an indication of the reduced demands placed on users during the operation of the ergonomic pipette model. This is significant as it indicates an advancement in pipette design and the reduction of the MSD risk associated with manual pipetting. In addition, users' preference for the ergonomic model highlights users' attitudes toward seeking comfort and reduced strain during pipetting. The importance of pipette preference and selection is emphasized by Hoskins & Erickson (1998) and Erickson & Smith (2007) who mention that pipette selection plays a pivotal role in reducing the risk associated with manual pipetting.

Contrary to the above-mentioned results, Lee & Jiang (1999) and Kim et al. (2020) found that ergonomically modified pipette models resulted in reduced muscle activity of all muscles tested, improved performance, reduced awkward postures, and favourable subjective responses in comparison to traditional mechanical models. The difference in results between this study and Lee & Jiang and Kim et al. (2020) can be attributed to the inaccurate calibration of the bi-axial goniometer and the manual processing of the EMG data which affected the deductions made on the biophysical responses measured. Discrepancies can also be attributed to the different methods used by Lee & Jiang (1999) and Kim et al. (2020). Furthermore, Sormunen & Nevala (2013) mention that factors such as preference and familiarity can influence objective and subjective measures. Thus, users' unfamiliarity with the Vista model could have impacted the biomechanical responses and may partly explain the observed differences between the subjective and objective measures.

Despite this, the ergonomic model was favourable at improving user comfort and usability without affecting performance. The main disadvantage of the pipette model was its weight and grip circumference which users found uncomfortable. These features might have also increased muscular loading and influenced wrist postures. According to Burt, (2016) pipette diameter affects muscle activity, and generally diameters between 2,54 cm and 3,81 cm are acceptable. Sormunen & Nevala (2013) propose that hand tools such as pipettes should be short and light (length of 22-23 cm and a weight of 68-76 g) with a compatible handle and should allow for grip variation in ambidextrous work. The Vista model had a grip circumference of 15,5 cm and a weight of 140 g, which exceed the recommended guidelines by Burt (2016) and Sormunen & Nevala (2013). This indicates that the Vista model might cause muscular strain to users and highlights the importance of a user-centred approach to tool design and considering factors such as hand anthropometry and user capabilities to the design of pipettes. In addition, user familiarity and preference should also be considered in pipette design.

5.5 Limitations of this study

There are several limitations associated with this study. These include limitations attributed to the surface EMG signal, experimental procedure, and sample characteristics.

5.5.1 Limitations of surface electromyography

During the measurement of maximal voluntary exertions, it was observed that some participants did not maximally exert themselves despite the practise sessions; this could be attributed to the fact that the muscle actions performed were awkward and strenuous for the participants (see Appendix Z for muscle actions). Given that muscle activity signals were normalised using maximal voluntary exertions, this could have altered the recorded muscle activity responses and impacted the deductions made. Furthermore, because the pipetting task was set to 80 cycles (40 cycles for each pipette model), muscle fatigue may have occurred, resulting in increased motor unit recruitment and muscle activity levels. Although the effect of fatigue was reduced to the best of the experimenter's ability (by allowing rest periods between pipetting tasks), the task's repetitiveness could not be avoided as the study attempted to mimic the repetitive nature of pipetting. Muscle activity responses might have also been impacted by crosstalk associated with surface electromyography. Since the muscles of the thumb and forearm are in proximity to one another and thus difficult to isolate, the detected EMG signals may have been influenced by muscle activity in adjacent muscles. Lastly, the manual processing of the EMG data (whereby periods of inactivity were manually cut out) might have also influenced the muscle activity results. However, given that every participant's data was processed the same way, the impact of this limitation on the data assessed was minimised.

5.5.2 Limitations of the electro-goniometer

Another limitation of this study is the error in the calibration of the bi-axial goniometer. The bi-axial goniometer was calibrated prior to testing by asking participants to assume neutral wrist postures with their palmar side of the hand facing downwards. This was not consistent because the neutral wrist postures were not standardised across participants, resulting in varying wrist posture measurements, which affected the conclusions drawn about the different pipette models. Furthermore, participants were given the freedom to move the pipetting equipment (i.e., sample containers and disposable buckets) to their liking, which influenced the wrist postures adopted and resulted in increased wrist posture variability.

5.5.3 Limitations of experimental design

This study was a simulated study that tested only one standard pipetting task and used water as the sample fluid. It did not consider the various tasks, sample fluids, and postures adopted by laboratory workers in situ. Laboratory workers work in biosafety cabinets and perform tasks which result in pipette operators adopting varying postures that influence the muscle activity and wrist posture joint angles. A variation in task environment might have also influenced user's perceived comfort and usability, and pipette preference. In addition, the current study did not consider thumb, forearm, and shoulder postures adopted during pipetting. These body regions have been reported to be strained during pipetting and associated with various repetitive strain injuries because of manual pipetting. Thumb and hand forces during pipetting were also not measured due to limited inputs in the datalogger system used to record biophysical outputs.

5.5.4 Limitations of sample

The small sample size of 20 participants, as well as the fact that some student participants did not have the required experience (due to the COVID-19 pandemic interfering with their practical pipetting experience) limited the results obtained. This is because participants with less pipetting experience may have applied more force and adopted more awkward postures during pipetting than experienced users, contributing to the large variation observed in the muscle activity and wrist posture results.

Furthermore, the small sample size might have affected the significance of the data collected.

Chapter 6

Conclusions and Recommendations

6.1 Conclusion

The results of this study highlight the effects of incorporating ergonomics into pipette design on performance, biomechanical and subjective aspects. The ergonomic pipette model in this study elicited the purpose of ergonomics as it partially reduced muscle activity, especially of the thumb muscles, and reduced radial deviation, without impacting performance. Furthermore, the Vista model improved subjective aspects as it was perceived to require less muscular effort during operation, and it was perceived to be more comfortable and associated with better usability features than the traditional pipette model.

Although the ergonomic pipette model rendered various benefits, the wide grip circumference and weight of the pipette were an issue especially to users with smaller hand dimensions. In addition, users' unfamiliarity with the Vista model affected the measured responses. This mismatch between pipette users' capabilities and the pipette increases muscular strain, awkward postures, and discomfort, and increases pipette user's risk of MSD development. Thus, pipette manufacturers should consider incorporating a user-centred approach whereby pipette specifications are matched with user's anthropometrics and capabilities (Pheasant & Haslegrave, 2018). Moreover, although the Vista model reduced various biomechanical responses, it was still found to expose users to increased static muscular loading and awkward wrist postures (especially increased wrist extension and ulnar deviation) attributed to the stabilization and operation of the pipette during the performance of pipetting tasks. This emphasizes that the design of pipettes should simultaneously consider the interaction between the task and tool, as well as the task and workspace, as these interactions contribute to the strain placed on users.

The outcomes of this study provide evidence in favour of the implementation of ergonomics to pipette design and propose the Vista model as a potential intervention to address and mitigate the ergonomic stressors associated with manual pipetting.

Furthermore, this study emphasizes the incorporation of a user-centred approach to pipette design.

6.2 Recommendations regarding pipette design

From the study, it can be deduced that an ergonomic modification to pipette design and pipette features may help reduce certain biomechanical risk factors associated with manual pipetting and improve subjective responses without impacting performance. The improvement is attributed to a change in key design features reported by Lee et al. (1999), Lu et al. (2008) and Sormunen & Nevala (2013), which include reduced plunger forces, improved handle design (the non-axial grip), and a shorter pipette length. Although the Vista model addresses several of the problem features associated with traditional axial pipettes, the wide grip diameter and heavy weight of the pipette model still pose a risk for increased muscular strain, awkward postures, user discomfort, and contribute to the MSD risk placed on pipette users. In addition, the results of this study highlight that because pipette operators use varying techniques to operate pipettes, this contributes to muscular strain and awkward postures. Thus, it is recommended that pipette manufacturers reduce the weight of pipettes and vary the grip diameter of pipettes to accommodate users with different hand sizes, and to cater for users with a wide range of physical characteristics, skills and individual or task-related requirements. Although it's unrealistic to design a pipette that is specific to every single user's capability, catering for the 5th, 50th, and 95th percentiles for men and women would be ideal (Pheasant & Haslegrave, 2018).

6.3 Recommendations for further research

This study highlights that pipette design and pipette features contribute significantly to the muscular loading, wrist postures, performance, and subjective responses of users. Despite the deductions made from this study, several limitations restrict the transferability of the results obtained. Thus, future investigations into pipette design and its effects on biomechanical, performance, and subjective responses are required to allow for the transferability of the data in situ. The research considerations can include the following aspects:

1. Reconducting this present study and ensuring that the assessment tools (such as the bi-axial goniometer) are calibrated properly to make accurate deductions.
2. Increasing the duration of pipetting tasks to assess the effects of the different pipette models over a duration of a work shift and to determine their effects on muscle fatigue.
3. Conducting a similar study in situ, with laboratory workers performing a variety of pipetting tasks and assuming varying postures to determine whether the results of this study are similar when laboratory workers use the different pipette models in a real-time work setting.
4. Additional muscles including the wrist, shoulder, and finger muscles should be tested to determine the effects of the different pipette models on the muscular strain placed on these muscles.
5. Future studies should consider analysing thumb, hand, shoulder, and forearm joint postures during pipetting using the different pipette models, as these body regions are often placed in awkward positions during pipetting.
6. The effects of pipette design on performance should be tested in more depth whereby the entire pipetting cycle (including volume adjustment) should be analysed. In addition, the accuracy with which pipetting tasks are performed using each pipette model should be assessed.
7. The effects of the different pipette models on grip strength should be tested to assess the degree of muscular strain attributed to the grip design.
8. Thumb force capacities and plunger operational forces should also be considered to infer the strain placed on the thumb joint during plunger manipulation of the different pipette models.
9. A range of traditional axial pipette models used in industry should be tested and compared to the ergonomic pipette model to ascertain whether the ergonomic pipette model is “better” than other traditional pipette models, as the traditional pipette model used in this study had technical modifications which rendered reduced muscular forces.
10. The use of the different pipette models over prolonged periods should be assessed to determine the onset of muscle fatigue associated with each pipette model, and RPE should be recorded during the performance of pipetting tasks to infer the development of perceived strain throughout pipetting tasks.

References

Akodu, A., Akinfeleye, A., Atanda, L., & Giwa, S. (2015). Work-related musculoskeletal disorders of the upper extremity with reference to working posture of secretaries. *South African Journal of Occupational Therapy*, *45*(3), 16–22. https://doi.org/10.17159/2310-3833/2015/V45N3/A4

AlNekhilan, A., AlTamimi, A., AlAqeel, B., AlHawery, A., AlFadhel, S., & Masuadi, E. (2020). Work-related musculoskeletal disorders among clinical laboratory workers. *Avicenna Journal of Medicine*, *10*(1), 29. https://doi.org/10.4103/ajm.ajm_67_19

Andersen, E. (2004). Clinical rounds: Hospital Link Laboratory Workers and Musculoskeletal Disorders-Examining Ergonomic Risk Factors and Solutions. *American association of occupational health nurse's journal*. 52(9), 366-367.Retrieved March 5, 2020, from http://www.niehs.nih.gov/odhsblergoguidlh.

Aptel, M., Claudon, L., & Marsot, J. (2002). Integration of ergonomics into hand tool design: Principle and presentation of an example. *International Journal of Occupational Safety and Ergonomics*, *8*(1), 107–115. https://doi.org/10.1080/10803548.2002.11076518

Asundi, K. R., Bach, J. M., & Rempel, D. M. (2005). Thumb force and muscle loads are influenced by the design of a mechanical pipette and by pipetting tasks. *Human Factors*, *47*(1), 67–76. https://doi.org/10.1518/0018720053653848

Baker, N. A., & Jacobs, K. (2010). Tele-Ergonomics: A Novel Approach to Computer Workstation Ergonomic Assessment and Modification. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *54*(9), 723–727. https://doi.org/10.1177/154193121005400909

Barr, A. E., & Barbe, M. F. (2002). Pathophysiological tissue changes associated with repetitive movement: A review of the evidence. *Physical Therapy,* 82 (2), 173–187. https://doi.org/10.1093/ptj/82.2.173

Björksten, M. G., Almby, B., & Jansson, E. S. (1994). Hand and shoulder ailments among laboratory technicians using modern plunger-operated pipettes. *Applied Ergonomics*, *25*(2), 88–94. https://doi.org/10.1016/0003-6870(94)90069-8

Bjorksten, M., & Jonsson, B. (1977). Endurance limit of force in long-term intermittent static contractions. *Scandinavian Journal of Work, Environment & Health*, *3*(1), 23–27. https://doi.org/10.5271/SJWEH.2795

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian Journal of Work, Environment & Health*, *16(1(*, 55–58. https://doi.org/10.5271/SJWEH.1815

Burt, C.M. (2016). Chapter 14: Biotechnology laboratories, promoting health and productivity with Ergonomics. In. A. Hedge (Ed), *Ergonomic workplace design for health, wellness, and productivity* (pp. 411-448). CRC Press Taylor and Francis Group. https://doi.org/10.1201/9781315374000

Cao, L., Wang, Y., Hao, D., Rong, Y., Yang, L., Zhang, S., & Zheng, D. (2017). Effects of force load, muscle fatigue, and magnetic stimulation on surface electromyography during side arm lateral raise task: A preliminary study with healthy subjects. *BioMed Research International,* 1-9*.* https://doi.org/10.1155/2017/8943850

Carayon, P., & Smith, M. J. (2000). Work organization and ergonomics. *Applied Ergonomics*, *31*(6), 649–662. https://doi.org/10.1016/S0003-6870(00)00040-5

Chowdhury, R., Reaz, M., Ali, M., Bakar, A., Chellappan, K., & Chang, T. (2013). Surface Electromyography Signal Processing and Classification Techniques. *Sensors*, *13*(9), 12431–12466. https://doi.org/10.3390/s130912431

Costello, K. J. (2005). The Evolution and Ergonomics of Pipetting. *Laboratory medicine,* 36(9), 533-536. https://doi.org/10.1309/92B6618PQMYU3KAX

Cram, J. R., & Kasman, G. S. (2011). The basics of surface Electromyography Cram's introduction to surface electromyography. In E. Crisswell (Ed*), Cram's Introduction to surface electromyography* (pp. 3-7). 2nd edition. Sudbury, Massachusetts: Jones and Bartlett Publishers.

Croasmun, J. T., & Ostrom, L. (2011). Using Likert-Type Scales in the Social Sciences. *Journal of Adult Education*, *40*(1), 19–22.

David, G., & Buckle, P. (1997). A questionnaire survey of the ergonomie problems associated with pipettes and their usage with specific reference to work-related upper limb disorders. *Applied Ergonomics*, *28*(4), 257–262. https://doi.org/10.1016/S0003-6870(97)00002-1

David, G. C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. *Occupational Medicine,* 55(3), 190–199. https://doi.org/10.1093/occmed/kqi082

Edgren, C. S., Radwin, R. G., & Irwin, C. B. (2004). Grip force vectors for varying handle diameters and hand sizes. *Human Factors*, *46*(2), 244–251. https://doi.org/10.1518/HFES.46.2.244.37337

El-Helaly, M., Balkhy, H. H., & Vallenius, L. (2017). Carpal tunnel syndrome among laboratory technicians in relation to personal and ergonomic factors at work. *Journal of Occupational Health*, *59*, 513–520. https://doi.org/10.1539/joh.16-0279-OA

Ellapen, M. T., Ellapen, T. J., & Paul, Y. (2021). The growth patterns of the medical technology profession in South Africa. *African Journal of Laboratory Medicine*, *10*(1), 1–5. https://doi.org/10.4102/AJLM.V10I1.1164

Erick, P. N., & Smith, D. R. (2011). A systematic review of musculoskeletal disorders among school teachers. *BMC Musculoskeletal Disorders*, *12*, 260. https://doi.org/10.1186/1471-2474-12-260

Erickson, J. G., & Smith, A.V. (2007). A biopharmaceutical breakthrough. *Occupational Health and Safety*, 76(6), 141-2, 144-5.

Erickson, J., & Woodard, B. (2001). Smart pipetting: Using Ergonomics to prevent injury. *Technical reports*, 2 (1), 1-4. Retrieved July 3rd, 2021, from https://lte-bg.com/wp-content/uploads/2016/08/Smart-Pipetting.pdf

Finneran, A., & O'Sullivan, L. (2013). Effects of grip type and wrist posture on forearm EMG activity, endurance time and movement accuracy. *International Journal of Industrial Ergonomics*, *43*(1), 91–99. https://doi.org/10.1016/j.ergon.2012.11.012

Foltran, F. A., Silva, L. C. C. B., Sato, T. O., & Coury, H. J. C. G. (2013). Wrist electrogoniometry: are current mathematical correction procedures effective in reducing crosstalk in functional assessment? *Brazilian Journal of Physical Therapy*, *17*(1), 32–40. https://doi.org/10.1590/S1413-35552012005000067

Fredriksson, K. (1995). Laboratory work with automatic pipettes: a study on how pipetting affects the thumb. *Ergonomics*, *38*(5), 1067–1073. https://doi.org/10.1080/00140139508925173

FrØkjaer, E., Hertzum, M., & Hornbæk, K. (2000). Measuring usability: Are effectiveness, efficiency, and satisfaction really correlated? *Conference on Human Factors in Computing Systems - Proceedings*, 345–352. https://doi.org/10.1145/332040.332455

Garcia, E. C., Kundu, I., Kelly, M. A., Skillman, S. M., & Frogner, B. K. (2021). The Clinical Laboratory Workforce: Understanding the Challenges to Meeting Current and Future Needs*. American Society for Clinical Pathology (Washington, DC) and Center for Health Workforce Studies,* University of Washington, Seattle, WA. *April 2021*. Retrieved 30th October 2022 from https://familymedicine.uw.edu/chws/publications/the-clinical-laboratory-workforce-understanding-the-challenges-to-meeting-current-and-future-needs/.

García, M. A. C., & Vieira, T. (2011). Surface electromyography: Why, when and how to use it. *Revista Portuguesa De Pneumologia*, 4, 17-28.

Gerleman, D.G., & Cook, T.M. (1992). Chapter four: Instrumentation. In. G.L. Soderberg (*ed*), *Selected topics in Surface Electromyography for use in the occupational setting: expert perspectives*, 43-67. U.S. Department of Health and Human services public health service, Centres for disease and control, National Institute for Occupational safety and Health, 91-100. https://www.humanics-es.com/SelectedTopicsEMGsNIOSH.pdf

Gohar, B., & Nowrouzi-Kia, B. (2022). The Forgotten (Invisible) Healthcare Heroes: Experiences of Canadian Medical Laboratory Employees Working During the Pandemic. *Frontiers in Psychiatry*, *13*, 854507. https://doi.org/10.3389/FPSYT.2022.854507/FULL

Gross, J.M., Fetto, J., & Rosen, E. (2009). *Musculoskeletal Examination* (3rd ed.). Chichester: John Wiley & Sons Ltd Publishers.

Hambali, R. H., Rahim, S. A. A., Azizan, N., Zali, Z., Akmal, S., & Zin, M. H. (2019). Analysis the Awkward Posture Ergonomic Risk and Workstation Improvement Simulation in Mechanical Assembly Manufacturing Industry using DelmiaV5. *IOP Conference Series: Materials Science and Engineering*, *705*(1). https://doi.org/10.1088/1757-899X/705/1/012044

Higgs, P., Young, V. L., Seaton, M., Edwards, D., & Feely, C. (1992). Upper extremity impairment in workers performing repetitive tasks. *Plastic and Reconstructive Surgery*, *90*(4), 614–620. https://doi.org/10.1097/00006534-199210000-00010

Holm, J. W., Mortensen, O. S., & Gyntelberg, F. (2016). Upper limb disorders among biomedical laboratory workers using pipettes. *Cogent Medicine*, *3*(1). https://doi.org/10.1080/2331205x.2016.1256849

Hoskins, D. B., & Erickson, J. (1998). Laboratory ergonomics. The wake-up call: A Case Study. *Chemical Health & Safety*., 5(1), 20-38. https://doi.org/10.1021/ACS.CHAS.8B05112

Hughes, L. E., & Babski-Reeves, K. (2016). Evaluation of an Electrogoniometer for Wrist Position Measurements. Proceedings: *Human factors and Ergonomics society 47th annual meeting,* 47(10), 1112-1116. https://doi.org/10.1177/154193120304701002

Jakobsen, M. D., Sundstrup, E., Persson, R., Andersen, C. H., & Andersen, L. L. (2014). Is Borg's perceived exertion scale a useful indicator of muscular and cardiovascular load in blue-collar workers with lifting tasks? A cross-sectional workplace study. *European Journal of Applied Physiology*, *114*(2), 425–434. https://doi.org/10.1007/S00421-013-2782-9/FIGURES/2

Jonsson, P. (2009). *Wrist and thumb joint postures and motions-measurements using electrogoniometry and EMG*. [Doctoral dissertation, Gothenburg University]. GUPEA. http://gupea.ub.gu.se/handle/2077/21193

Joseph, B., & Joseph, M. (2016). The health of the healthcare workers. *Indian Journal of Occupational and Environmental Medicine*, *20*(2), 71. https://doi.org/10.4103/0019-5278.197518

Joshi, A., Kale, S., Chandel, S., & Pal, D. (2015). Likert Scale: Explored and Explained. *British Journal of Applied Science & Technology*, *7*(4), 396–403. https://doi.org/10.9734/BJAST/2015/14975

Keir, P. J., Bach, J. M., Hudes, M., & Rempel, D. M. (2007). Guidelines for wrist posture based on carpal tunnel pressure thresholds. *Human Factors*, *49*(1), 88–99. https://doi.org/10.1518/001872007779598127

Kendall, F., McCreary, E. K., Provance, P. G., Rodgers, M. M., & Romani, W. A. (2005) *Muscle testing and function with posture and pain* (5th ed)*.* Lippincott Williams & WilkinS, Baltimore, MD. Retrieved September 4, 2022, from https://scirp.org/reference/referencespapers.aspx?referenceid=47898.

Ketola, R., Toivonen, R., & Viikari-Juntura, E. (2010). Interobserver repeatability and validity of an observation method to assess physical loads imposed on the upper extremities, *44*(2), 119–131. https://doi.org/10.1080/00140130118669

Kim, E., Aqlan, F., & Freivalds, A. (2020). Development of an ergonomic four-finger-push manual pipette design. *Applied Ergonomics*, *85*. https://doi.org/10.1016/J.APERGO.2020.103045

Krawczyk, S. (2012). Chapter 6: Psychophysical Methodology and the Evaluation of Manual Materials Handling and Upper Extremity Intensive Work. In. A. Bhattacharya, & J.D. McGlothin, J.D. (eds), *Occupational Ergonomics: Theory and Applications, Second Edition*, 173–203. Marcel Dekker Inc, New York. https://doi.org/10.1201/B11717-10/psychophysical-methodology-evaluation-manual-materials-handling-upper-extremity-intensive-work-Sheila-Krawczyk

Kuriki, H. U., Mícolis De Azevedo, F., Sanae, L., Takahashi, O., & Mello, M. (2012). Chapter 3: The Relationship Between Electromyography and Muscle Force. In M. Schwartz (Ed), *EMG Methods for evaluating muscle and nerve function.* DOI: 10.5772/25381. Retrieved January 30, 2023, from www.intechopen.com

Lacerda, E. M., Nácul, L. C., Augusto, L. G. D. S., Olinto, M. T. A., Rocha, D. C., & Wanderley, D. C. (2005). Prevalence and associations of symptoms of upper extremities, repetitive strain injuries (RSI) and “RSI-like condition”. A cross sectional study of bank workers in Northeast Brazil. *BMC Public Health*, *5*, 107. https://doi.org/10.1186/1471-2458-5-107

Lasec. (2015). *Lasec Adjustable Volume Pipette: User's gude*. France: Author.

Lee, Y. H., & Jiang, M. S. (1999). An ergonomic design and performance evaluation of pipettes. *Applied Ergonomics*, *30*(6), 487–493. https://doi.org/10.1016/S0003-6870(99)00011-3

Lestari, F., Bowolaksono, A., Yuniautami, S., Wulandari, T. R., & Andani, S. (2019). Evaluation of the implementation of occupational health, safety, and environment management systems in higher education laboratories. *Journal of Chemical Health and Safety*, *26*(4–5), 14–19. https://doi.org/10.1016/J.JCHAS.2018.12.006

Lichty, M. G., Janowitz, I. L., & Rempel, D. M. (2011). Ergonomic evaluation of ten single-channel pipettes. *Work, 39*(2), 177–185. https://doi.org/10.3233/WOR-2011-1164

Lintula, M., & Nevala, N. (2006). Ergonomics and the usability of mechanical single-channel liquid dosage pipettes. *International Journal of Industrial Ergonomics*, *36*(3), 257–263. https://doi.org/10.1016/j.ergon.2005.06.011

Lu, M. L., James, T., Lowe, B., Barrero, M., & Kong, Y. K. (2008). An investigation of hand forces and postures for using selected mechanical pipettes. *International Journal of Industrial Ergonomics*, *38*(1), 18–29. https://doi.org/10.1016/j.ergon.2007.08.006

Malchaire, J., Cock, N., Vergacht, S. (2001). Review of the factors associated with musculoskeletal problems in epidemiological studies. *International Archives of Occupational and Environmental Health,* 74, 79-90. https://doi.org/10.1007/s004200000212

Marras, W. S. (2016). Overview of Electromyography in Ergonomics. *Proceedings of the Human factors and Ergonomics Society Annual meeting,* 44(30) 534–536. Columbus, Ohio. https://doi.org/10.1177/154193120004403037

McGlothin, J.D., & Hales, T.R. (1996). NIOSH Health Hazard evaluation report of a biological laboratory No. 95-0294-2594. *Scientific Application International Corporation*. Fredrick, Maryland. https://www.cdc.gov/niosh/hhe/reports/pdfs/1995-0294-2594.pdf?id=10.26616/NIOSHHETA9502942594

Merletti, R., Rainoldi, A., & Farina, D. (2001). Surface electromyography for noninvasive characterization of muscle. *Exercise and Sport Sciences Reviews*, *29*(1), 20–25. https://doi.org/10.1097/00003677-200101000-00005

Mohammad, Y. A. A. (2005). Anthropometric characteristics of the hand based on laterality and sex among Jordanian. *International Journal of Industrial Ergonomics*, *35*(8), 747–754. https://doi.org/10.1016/J.ERGON.2004.11.005

Mukhtad, A. A., Abdulkareem Aminese, H., Mansor, M. A., Salam Mansour, H., & Elmesmary, H. A. (2018). Ergonomic Risk Assessment among Healthcare Laboratory

Technicians in Benghazi Medical Centre. *International Journal of Advance Research and Development,* 3(3), 318-327.

Nasrallah, I. M., El Kak, A. K., Ismaiil, L. A., Nasr, R. R., & Bawab, W. T. (2022). Prevalence of Accident Occurrence Among Scientific Laboratory Workers of the Public University in Lebanon and the Impact of Safety Measures. *Safety and Health at Work*, *13*(2), 155–162. https://doi.org/10.1016/J.SHAW.2022.02.001

Penkala, S., El-Debal, H., & Coxon, K. (2018). Work-related musculoskeletal problems related to laboratory training in university medical science students: A cross sectional survey. *BMC Public Health*, *18*(1). https://doi.org/10.1186/s12889-018-6125-y

Pheasant, S. (1996). *Bodyspace: anthropometry, ergonomics, and the design of work*. London: CRC Press. 244.https://doi.org/10.1201/9781482272420

Pheasant, S., & Haslegrave, C. M. (2018). *Bodyspace:: Anthropometry, Ergonomics and the Design of Work* (3rd ed.). *Boca Raton: CRC Press.* https://doi.org/10.1201/9781315375212

Radwin, R.G. (2003). Hand Tools: Design and Evaluation. *Occupational ergonomics: Engineering, and administrative controls*. 5(1).

Rainin. (2016). *Pipetting, Ergonomics, and you*. RAININ/Mettler Toldeo company paper.TR-2001:8:01.20M.Retrieved 13 April, 2020, from https://risk.arizona.edu/sites/default/files/pipettingergonomics.pdf. Last Accessed 31 January 2022.

Rash, G. S. (1999). Electromyography Fundamentals. *International Encyclopaedia of Ergonomics and Human factors.* Retrieved 17 May 2021, from https://www.semanticscholar.org/paper/Electromyography-Fundamentals-Rash/7161eabf4021e7de8fc4eb3a9456ea07e7e44df1.

Reaz, M. B. I., Hussain, M. S., & Mohd-Yasin, F. (2006). Techniques of EMG signal analysis: Detection, processing, classification and applications. *Biological Procedures Online*, *8*(1), 11–35. https://doi.org/10.1251/bpo115

Rempel, D., Burt, C., Janowitz, I., Junge, M., & Pollard, M. (2008). Ergonomics in the biosciences. *Proceedings of the Human Factors and Ergonomics Society*. New York, *2*, 1073–1077, September 2008. https://doi.org/10.1177/154193120805201516

Ritchie, C. (2012). Rating of Perceived Exertion (RPE). In *Journal of Physiotherapy*, 58(1). https://doi.org/10.1016/S1836-9553(12)70078-4

Robertson, D. G. E, Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2014). *Research Methods in Biomechanics (*2nd ed.). USA: Human Kinetics*.*

Roman-Liu, D., Bugajska, J., & Tokarski, T. (2014). Comparative study of upper limb load assessment and occurrence of musculoskeletal disorders at repetitive task workstations. *Industrial Health*, *52*(6), 461–470. https://doi.org/10.2486/indhealth.2013-0232

Roquelaure, Y., Ha, C., Rouillon, C., Fouquet, N., Leclerc, A., Descatha, A., Touranchet, A., & Goldberg, M. (2009). Risk Factors for Upper-Extremity Musculoskeletal Disorders in the Working Population. *Arthritis Rheumatoid*, 61(10),1425-1434.https://doi.org/10.1002/art.24740

Selvaraj, N. (2018). *Biomechanics of Thenar muscles and transverse carpal ligament during pipetting.* (Document No. csu1528985532616584) [Masters thesis, Cleveland State University]. OhioLink Electronic Theses and dissertations Center. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=csu1528985532616584&disposition=inline

Silverstein, B. A., Fine, L. J., & Armstrong, T. J. (1986). Hand wrist cumulative trauma disorders in industry. *British Journal of Industrial Medicine*, 43(11), 779-784. https://doi.org/10.1136%2Foem.43.11.779

Sirajudeen, M. S., Alaidarous, M., Waly, M., & Alqahtani, M. (2018). Work-related musculoskeletal disorders among faculty members of college of Applied Medical Sciences, Majmaah University, Saudi Arabia: A cross-sectional study. *International Journal of Health Sciences*, *12*(4), 18-25. /pmc/articles/PMC6040859/

Sormunen, E., & Nevala, N. (2013). User-oriented evaluation of mechanical single-channel axial pipettes. *Applied Ergonomics*, *44*(5), 785–791. https://doi.org/10.1016/J.APERGO.2013.01.009

Steele, J., Fisher, J., Mckinnon, S., & Mckinnon, P. (2017). Differentiation between perceived effort and discomfort during resistance training in older adults: Reliability of trainee ratings of effort and discomfort, and reliability and validity of trainer ratings of trainee effort. *Journal of Trainology*, *6*, 1–8. http://dx.doi.org/10.17338/trainology.6.1_1

Trimmel, M., & Trimmel, K. (2017). Rating Comfort and Every-Day Mood States (TRIM-S): Comparing Likert Scales with Visual Analog Scales (VAS) and Relations to Cardiovascular Response. *The Ergonomics Open Journal*, *10*(1), 14–28. https://doi.org/10.2174/1875934301710010014

Unyi, M., & Asato, K. (2015). *Ergonomic Modification to Pipetting to Reduce Discomfort and Muscle Strain.* [Unpublished Master's Thesis, University of Puget Sound] Institutuinal repository at the Univerity of Puget Sound. https://soundideas.pugetsound.edu/ms_occ_therapy/116

van Tulder, M., Malmivaara, A., & Koes, B. (2007). Repetitive strain injury. *Lancet* 369(9575), 1815–1822. https://doi.org/10.1016/S0140-6736(07)60820-4

VistaLab Technologies *(2001). Results of an Investigation into the Design of an Ergonomic Pipette VISTALAB TECHNOLOGIES*. Retrieved on 25th June 2021, from https://vistalab.com/wp-content/uploads/2018/10/ResultsofanInvestigationintotheDesignofanErgonomicPipette_final.pdf.

Werner, R., Armstrong, T. J., Bir, C., & Aylard, M. K. (1997). Intracarpal canal pressures: The role of finger, hand, wrist and forearm position. *Clinical Biomechanics*, *12*(1), 44–51. https://doi.org/10.1016/S0268-0033(96)00044-7

Williams, N. (2017). The Borg Rating of Perceived Exertion (RPE) scale. *Occupational Medicine*, *67*(5), 404–405. https://doi.org/10.1093/OCCMED/KQX063

Wu, J. Z., Sinsel, E. W., Gloekler, D. S., Wimer, B. M., Zhao, K. D., An, K. N., & Buczek, F. L. (2012). Inverse dynamic analysis of the biomechanics of the thumb while pipetting: A case study. *Medical Engineering and Physics*, *34*(6), 693–701. https://doi.org/10.1016/j.medengphy.2011.09.012

Wu, J. Z., Sinsel, E. W., Shroyer, J. F., Warren, C. M., Welcome, D. E., Zhao, K. D., An, K. N., & Buczek, F. L. (2014). Analysis of the musculoskeletal loading of the thumb during pipetting - A pilot study. *Journal of Biomechanics*, *47*(2), 392–399. https://doi.org/10.1016/j.jbiomech.2013.11.015

You, D., Smith, A. H., & Rempel, D. (2014). Meta-Analysis: Association Between Wrist Posture and Carpal Tunnel Syndrome Among Workers. *Safety and Health at Work*, *5*(1), 27. https://doi.org/10.1016/J.SHAW.2014.01.003

ARTEL. (n.d.). *Lab report 3: Pipette Use and Ergonomics.* https://www.artelcollearning-centre/pipette-use-andergonomics/. Accessed on 13 April 2022.

Integra. *(n.d).Why ergonomic pipetting matters!* Retrieved March 2, 2022, from https://www.integra-biosciences.com/global/en/stories/why-you-should-care-about-ergonomic-pipetting-your-lab

Canadian Centre for Occupational Health and Safety. (n.d.). *Laboratory Technician and Technologist : OSH Answers*. Retrieved September 19, 2022, from https://www.ccohs.ca/oshanswers/occup_workplace/labtech.html.

National Institute for communicable diseases. (n.d.). *National and provincial trends of COVID-19 cases in South Africa Epidemiologic week Daily cases Cumulative cases*. (n.d.). Retrieved July 14, 2022 from https://www.nicd.ac.za/media/alerts/

National Laboratory service. (n.d.). *About Us – National Health Laboratory Service*. Retrieved December 2, 2021, from https://www.nhls.ac.za/about-us/

Appendices

Appendix A: Borg Rating of Perceived Exertion (RPE) scale (Ozdol et al., 2018)

Rating	Descriptor
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very Hard
18	
19	Extremely hard

Appendix B: Questions used for subjective measures of comfort and usability using a 5-point rating scale.

The following questions were answered using a 5-point rating scale where: 1= Very uncomfortable 2= Uncomfortable 3= Neutral 4= Comfortable 5= Very comfortable

Q1. Ease of pipette grip?

Q2. Ease in performing pipetting task using pipette

Q.3. Location of aspiration and dispensation plunger

Q.4. Ease of tip application

Q.5. Location of ejection button

Q.6. Ease to eject tip

Q.7. Thumb force exerted for plunger manipulation

Q.8. Overall fit of pipette in hand

Q.9. Weight of pipette in hand

Q.10. Overall preference (comfort and efficiency)

Appendix C: Summary of the characteristics of different pipette models available in the market.

	Traditional Pipettes			Ergonomic pipettes				
Pipette Model	Gilson Pipetteman Neo	Eppendorf Research Plus	Lasec AV* (Figure 5)	BioHit mLine Sartorius	Thermo Fisher Finnipipette F1	VistaLab Ovation Bionatural* (Figure *6*)	Rainin Pipet-Lite	Rainin Pipet-plus
Weight (g)	143	91	N/A	79	68	159	108	75
Length (cm)	24.3	20.8	N/A	22.5	22.2	14.8	21.4	22.5
Grip circumference (cm)	10	N/A	N/A	9.4	9.3	N/A	9.5	N/A
Tip ejection	4.21	2.17	N/A	2.90	N/A	0.44	0.6	0.6

Force (kg)								
Tip insertion force (kg)	5.5	5.5	N/A	N/A	N/A	N/A	Depends on force applied by user (Less than 1 kg)	Less than 1 kg
Plunger operational force (Kg)	0.71	0.69	N/A	0.3-1.2	N/A	0.43	0.56	N/A
Aspiration force (Kg)	N/A	N/A	N/A	N/A	N/A	0.56	N/A	N/A
Blowout force (Kg)	3.30	0.7-1.5	N/A	1.2	N/A	1.7	1.76	1
Shape	Axial	Axial	Axial	Axial	Axial	Non-axial	Axial	Axial
Finger hook	N/A	N/A	Fixed finger hook	Finger support	Rotating finger rest	N/A	Adjustable finger hook	N/A

Plunger operation system	N/A	N/A	Air displacement mechanism	Patented spring mechanism	N/A	N/A	N/A	Magnetic assist reduces operating forces
Tip system	Traditional tip system	Traditional tip system	Traditional tip system	N/A	Clip tip system	N/A	Lite TouchTip ejection System (reduces force by 65%)	Lite Touch Tip ejection system (reduces forces by 85%)
Additional Ergonomic features		Friction seal	Adjustable ejection button	OptiLoad system (tips sealed with constant force)		Neutral hand and wrist posture for handle grip	Audible feedback	

Manufacturer Source		https://www.eppendorf.com/product-media/doc/en/129417_Application-Note/Eppendorf_Liquid-Handling_Application-Note_197_Research-plus-Eppendorf-Research-plus-pipette-lightweight_reliable-ergonomic.pdf	Lasec (2015)	https://www.vivaproducts.com/downloads/biohit-mechanical-pipette-raising-standards.pdf	https://assets.thermofisher.com/TFS-Assets/LCD/brochures/Finnpipette-F1-and-Finnpipette-F2-brochure.pdf	https://vistalab.com/wp-content/uploads/2016/02/Ovation-QS-Operators-Guide_RevH.pdf		https://www.pipette.com/Manuals/pipet_plus_manual.pdf
Journal source	Lichtyet al., (2011) and Sormunen & Nevala (2013)	Lichty et al., (2011); Sormunen & Nevala (2013)		Lichty et al., (2011)	Lichty et al., (2011); Sormunen & Nevala (2013)	Sormunen & Nevala (2013)	Lichty et al., (2011) and Costello (2005)	Lichty et al., (2011); Sormunen & Nevala (2013) Pipetting, Ergonomics, and you, n.d.

*Pipette models used in this study N/A = Not available

Appendix D: Ethical clearance letter

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Rhodes University Human Research Ethics Committee
PO Box 94, Makhanda, 6140, South Africa
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e: ethics-committee@ru.ac.za
NHREC Registration number: RC-241114-045

https://www.ru.ac.za/researchgateway/ethics/

3 May 2022

Bonolo MASOKA

Email: g17m9701@campus.ru.ac.za

Review Reference: 2022-5434-6702

Dear Bonolo Masoka

Title: A comparison of the muscle activity, wrist position, plunger operational pressure, performance time, and subjective responses between traditional and ergonomic pipettes

Researcher: Ms Bonolo Masoka

Supervisors: Dr Swantje Wells, Mr Luke Goodenough

This letter confirms that the above research proposal has been reviewed and **APPROVED** by the Rhodes University Human Research Ethics Committee (RU-HREC). Your Approval number is: 2022-5434-6702

Approval has been granted for 1 year. An annual progress report will be required in order to renew approval for an additional period. You will receive an email notifying you when the annual report is due.

Please ensure that the ethical standards committee is notified should any substantive change(s) be made, for whatever reason, during the research process. This includes changes in investigators. Please also ensure that a brief report is submitted to the ethics committee on the completion of the research. The purpose of this report is to indicate whether the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the ethical standards committee should be aware of. If a thesis or dissertation arising from this research is submitted to the library's electronic theses and dissertations (ETD) repository, please notify the committee of the date of submission and/or any reference or cataloguing number allocated.

Sincerely,

Arthur Webb

Prof Arthur Webb

Chair: Rhodes University Human Research Ethics Committee, RU-HREC

cc: Ms Danielle de Vos - Ethics Coordinator

Appendix E: Gatekeeper approval letter

RHODES UNIVERSITY
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1 June 2022

Dr S Wells
Human Kinetics and Ergonomics

Dear Dr Wells

REQUEST FOR GATEKEEPERS PERMISSION TO CONDUCT RESEARCH WITH RHODES UNIVERSITY STUDENTS

Name of research proposal: A comparison of the muscle activity, wrist position, plunger operational pressure, performance time, and subjective responses between traditional and ergonomic pipettes.

This serves to confirm that you have been granted permission to conduct your proposed research at Rhodes University as requested.

Kindly be advised that the University is not obliged to make any arrangements in terms of this research, and that the onus is on the researcher. It is also your responsibility to protect the integrity of the University in the manner in which you collate and engage the data.

This letter is valid from 1 June 2022 to 31 May 2024.

Yours sincerely

AL Moodly

Professor A.L Moodly REGISTRAR

Appendix F: Anthropometric measurements and descriptions as described by Mohammed (2005)

Anthropometric measurement	Measurement description
Hand length	Measured from the tip of the phalanx of the third digit to the inter stylion landmark (the distal crease of the wrist).
Palm length	Measured from the root of the palm to the root of the middle finger.
Hand width/breadth	Measured at the level of maximum bulge of the palm excluding the thumb (at the metacarpophalangeal joint level of the second and fifth digits).
Palm circumference	Measurement of the contour of the hand at the palm level. (Measured at the metacarpophalangeal joint level of the second and fifth digits).
Thumb length	Measured from the top of the thumb to the metacarpophalangeal joint.
Hand thickness	Measured at the middle portion of the palm transversely (circumference passing over the metacarpal joints).

Appendix G- Letter of information

Dear Sir/Madam

Thank you for volunteering to participate in this study which aims to compare the muscle activity, wrist posture, plunger operation pressure and perceptual responses of different pipette models. This letter serves to inform you about the purpose of this study, protocols, and experimental procedure, as well as the risks and benefits associated with this study. Could you kindly read this letter of information carefully and complete the accompanying consent form. Kindly ensure that you understand the contents of this letter and should you have any questions or queries regarding this study and its protocol, do not hesitate to direct them to the researcher or supervisor/co-supervisor. Your confidentiality and anonymity will be maintained throughout the study. Thank you for your participation and co-operation.

Purpose of the study

The purpose of this study is to compare the muscle activity, wrist posture, plunger operation pressure and perceptual responses of different pipette models. This will involve the use of psychophysical, biomechanical and subjective measures. Electromyography will be used to measure muscle activation, Electrogoniometry will be used to measure wrist postures, and the Rating of perceived exertion scale as well as a 5-pont rating scale will be used to measure perceived exertion and comfortability during pipetting using different pipette models. The study will simulate laboratory conditions of a pipette workstation. You will be required to perform the pipette cycle (tip insertion, fluid aspiration, fluid dispensation, and tip ejection) using the different pipette models with electrodes attached to your hand-arm muscles, and a goniometer attached to your wrist You will also be required to report your perceived exertion of each pipette model at the level of your hand, thumb, wrist, and forearm as well as rate the level of comfortability of each pipette model using a 5-point rating scale.

Procedure

You will be required to attend a single 15–30-minute session at the Human and Kinetics and Ergonomics department. In this session you will be required to perform a short habituation whereby you will familiarise yourself with the different pipette models, pipette functions, and pipette cycle. The researcher will direct you and verbally inform you about the experimental protocol and procedure. After the completion of the habituation, the experimental procedure will be conducted. You will be required to place eight pairs of electrodes over the surface of your Abductor Pollicis Longus, Abductor pollicis brevis, Flexor pollicis longus, Flexor pollicis brevis, Opponnens pollicis, Brachioradialis, Extensor pollicis brevis and Extensor pollicis longus muscle sites before performing the pipetting task. Prior to attaching these electrodes to the respective muscle sites, you will be required to clean these skin surfaces using alcohol and shave off any excessive hair. You will be required to perform three intervals of maximal voluntary exertions for each muscle by performing various limb movements and maximally exertions against a resistance. A goniometer will be placed between the distal phalanx of your first digit and the wrist of your dominant (pipetting) hand. You will then perform the pipette cycle (tip insertion, fluid aspiration, fluid dispensation, and tip ejection) for three intervals using each pipette model. After completing each pipetting condition, you will be asked to rate your perceived exertion at the level of your hand, thumb, wrist, and forearm for each pipette model using the RPE scale, as well as rate the level of comfortability using a 5-point rating scale. During the entire session you will be required to wear a mask and frequently sanitize your hands to comply with the COVID-19 regulations.

Risks and benefits

The chances of injury associated with this study are very low as the methods used are non-invasive and safe. In addition, the researcher will ensure your safety and comfort throughout the protocol by asking you how you feel. The possible risks are that you may experience an allergic reaction to the adhesive of the Electromyography electrodes. If this happens, electrodes with a different material will be used and the allergic reaction should subside within a couple of days. Another potential risk is the development of muscular discomfort due to unfamiliar posture and movement; this will be mitigated by limiting testing to 1 hour, and should you feel unable to complete the protocol, you will be allowed to withdraw from the study. Lastly, there is the risk of contracting COVID 19 however, this will be mitigated by maintaining social distancing in the lab, limiting the number of people to two people in the lab, wearing of masks at all times, and sanitizing of hands upon arrival into the lab and at various intervals throughout testing. Workbench surfaces and equipment used will also be sanitized prior to use.

The benefits of this study include learning a new laboratory technique and how to use a mechanical pipette. In addition, you will be contributing to the understanding of the risk factors associated with pipette design which contribute to the occurrence of MSDs in laboratories. You will also be contributing towards a study that can help in the redesign of pipette features which contribute to the MSD risk associated with manual pipetting, through the assessment and analysis of the muscular strain, awkward wrist postures, plunger operation forces and perceptual responses of different pipette models. Lastly, deductions from this study can be used in further interventions to redesign pipette tasks or pipettes as well as the selection of ergonomically safe pipettes and in interventions to improve overall Ergonomics safety in laboratories.

Your participation is greatly appreciated.

Regards

Bonolo Masoka.

Appendix H – Consent declaration

PARTICIPANT INFORMED CONSENT DECLARATION

(To be signed by research participants)

Research Project Title: A comparison of the muscle activity, wrist posture, time to task completion, and subjective responses between a traditional pipette and an ergonomic pipette.

Bonolo Masoka from the Department of Human Kinetics and Ergonomics, Rhodes University, has requested my permission to participate in the above-mentioned research project.

The nature and the purpose of the research project and of this informed consent declaration have been explained to me in a language that I understand.

I am aware that:

1. The purpose of the research project is to compare and assess the muscle activity, wrist posture, time to task completion, and subjective responses between a traditional pipette and an ergonomic pipette. This is to measure and compare the ergonomic risk associated with each pipette model, and to determine if the ergonomic pipette model can be used as a potential intervention to reduce the risk of Musculoskeletal development associated with manual pipetting.

2. Rhodes University has given ethical clearance to this research project ***(2022-5434-6702)*** and I have seen/may request to see the clearance certificate by contacting the Ethics Coordinator (ethics-committee@ru.ac.za).

3. By participating in this research project, I will be contributing towards a study that will help further the understanding of risk factors associated with pipette design and a study that can help in the redesign of pipette features that contribute to the MSD risk associated with manual pipetting. In addition, deductions from this study can be used in further studies or interventions to redesign pipettes and pipetting tasks, as well as promote the use of ergonomically safe pipettes to reduce the prevalence of MSDs amongst laboratory workers.

4. I will participate in the project by attending a 90-minute session that includes habituation and testing. During the habituation session I will be required to familiarize myself with each pipette model and pipette a random volume of water at least 2 times using each model. I will then allow the researcher to take anthropometric measurements of my hand using a tape measure, ruler, and calipers. I will also allow the researcher to prepare my skin surface for electrode placement, place electromyography electrodes on my hand-arm muscles and perform maximal voluntary contractions as directed by the researcher. I will allow for the placement of electrogoniometer end-blocks on the posterior side of my hand, over my third

metacarpal and the midline of my forearm. During the experimental procedure, I will be required to select one of the pipette models, insert a tip, aspirate fluid from a sample container, dispense the sample into an Eppendorf tube, and eject the tip. I'll be required to repeat this process 40 times, so that 40 Eppendorf tubes are filled with sample fluid. I will then be required to perform the same pipetting task using the remaining pipette model. I will perform the pipetting tasks while electromyography electrodes are attached to my hand-arm muscles and electrogniometer end-blocks are attached to my dominant hand. The time taken to perform the pipetting tasks using each pipette model will be measured using a stopwatch. I will also be required to provide subjective responses and ratings for each pipette model upon completion of the pipetting task. I will use the Rating of perceived Exertion (RPE) scale to rate my perceived exertion of each pipette model at the level of my hand, wrist, thumb, and forearm. I will also answer questions relating to the comfort and usability of the pipette features for each pipette model, by ranking my responses from 1 (very uncomfortable) to 5 (very comfortable). I will carry out the experimental procedure and pipetting task as instructed by the researcher. Images of me performing the pipetting task may be captured by the researcher, however the researcher will ask for my consent prior to this. The images will be used in the report and my identity will be kept anonymous.

5. My participation is entirely voluntary and should I at any stage wish to withdraw from participating further, I may do so without any negative consequences.

6. I will not be compensated for participating in the research, but my out-of-pocket expenses will be reimbursed.

7. The following risks are associated with my participation: The risk of injury associated with this study is very low as the methods used are safe and non-invasive.

   - The possible risks are that you may experience an allergic reaction to the adhesive of the electromyography electrodes. To mitigate this risk, people with known allergies to plasters will be excluded from the study as the adhesive material used in the electrodes is similar to those of certain types of plasters. Should there be skin reactions to the electrode adhesive, this is transient and can heal out in a couple of days (There have been no reports in literature about allergic reactions more severe than a slight skin irritation).

   - There is a risk of experiencing minor cuts, as the region where the EMG electrodes will be placed has to be shaved and abraded to prevent interference with the EMG signal and to prevent participants from experiencing pain upon the removal of the electrodes. Only individuals with excess hair at the regions of interest with be shaved and a new razor will be used for each person. The regions to be shaved will also be cleaned and disinfected to reduce the risk of infection, minor cuts, or skin abrasions. Injured or cut surfaces will be disinfected and treated with an antiseptic agent and plaster.

   - Another potential risk is the development of muscular discomfort or strain due to the repetitive nature of the pipetting task, the awkward postures adopted during pipetting, and the performance of maximal voluntary muscle exertions. The intensity of muscle strain and discomfort will be minimized by only testing apparently healthy participants and by limiting testing to 90 minutes.

- There is also the risk of COVID however, this will be mitigated to the best levels by ensuring social distancing in the lab, limiting the number of people to two people in the lab, wearing of masks at all times, sanitizing of hands and equipment at regular intervals throughout testing, and ensuring that participants have been screened for COVID prior to testing.

8. The Researcher intends to publish the research results in the form of a master's thesis. However, confidentiality and anonymity of records will be maintained, and my name and identity will not be revealed to anyone who has not been involved in conducting the research, *unless I indicate to the contrary/recognise that as a public figure, my identity will inevitably be/become known in which case I agree to and accept the loss of confidentiality.*

9. In terms of the Protection of Personal Information Act, it remains my right to request the Researcher to provide me with a detailed explanation of exactly how confidentiality and anonymity will be achieved. I may request to know how my personal information will be stored securely, for how long it will be stored, and whether it is likely to be used again in further research.

10. In terms of the Protection of Personal Information Act, I possess the right to receive feedback about this research. This will take the form of a brief email indicating the main findings of this study and the implications of the results, *unless I elect not to receive feedback.*

11. Any further questions that I might have regarding the research, or my participation will be answered by Bonolo Masoka (g17m9701@ru.ac.za).
12. By signing this informed consent declaration, I am not waiving any legal claims, rights or remedies.

13. A copy of this informed consent declaration will be given to me, and the original will be kept on record.

I, ……………………………………………………………………………, have read the above information / confirm that the above information has been explained to me in a language that I understand, and I am aware of this document's contents. I have asked all the questions that I wished to ask, and these have been answered to my satisfaction. I fully understand what is expected of me during the research.

I have not been pressurised in any way and I voluntarily agree to participate in the above-mentioned project.

I **agree/disagree** (SELECT APPLICABLE) to the Researcher's request to take photographs and/or videos of me as part of this research project, recognising that agreement here is likely to raise the risk of compromising my anonymity and that steps will be taken to ensure this does not happen if my approval is granted.

I **agree/disagree** to the Researcher's request to voice record my comments and opinions during interviews, the purpose of which is to ensure the accurate recording of my views. Furthermore, I have the right to request a copy of interview transcriptions to confirm that my opinions are accurately recorded.

…………………………………. …………………………..

Participants signature **Date**

Appendix I: Data recording sheet

Participant	
Gender	
Pipetting Experience	
Hand length (mm)	
Palm length (mm)	
Hand width (mm)	
Palm circumference (mm)	
Thumb length (mm)	
Hand thickness (mm)	

Table 2. Recording of RPE's for the traditional pipette and the ergonomic pipette model

	RPE @ hand	RPE @ wrist	RPE @ thumb	RPE @ forearm
Traditional pipette				
Ergonomic pipette				

Participants were required to answer the following questions by rating the answer from 1 to 5, whereby 1 represents very uncomfortable and 5 represents very comfortable. Participants were required to answer the questions for both the pipette models.

1 = Very uncomfortable; **2=Uncomfortable; 3=Neutral**; **4= Comfortable 5=Very comfortable**

Question	Traditional pipette					Ergonomic pipette				
	1	2	3	4	5	1	2	3	4	5
Ease of pipette grip?										
Ease in performing pipetting task using pipette										
Location of aspiration and dispensation plunger										
Ease of tip application										
Location of ejection button										
Ease to eject tip										
Thumb force exerted for plunger manipulation										
Overall fit of pipette in hand										
Weight of pipette in hand										
Overall preference (comfort and efficiency)										

Appendix J: Cut off thresholds for muscle activity levels during the use of two different pipette models.

Participants	Cut off threshold	
	Lasec	Vista
1	0,033	0,0482
2	0,04	0,052
3	0,01	0,073
4	0,0196	0,0095
5	0,0092	0,0153
6	0,06	0,038
7	0,0353	0,0153
8	0,1	0,0092
9	0,0438	0,0083
10	0,0315	0,0786
11	0,0842	0,0275
12	0,0216	0,0552
13	0,0382	0,05132
14	0,004	0,0116
15	0,1183	0,02
16	0,0191	0,0062
17	0,0385	0,0085
18	0,0618	0,0078
19	0,064	0,0677
20	0,0657	0,04

Appendix K: Statistical analysis results of the muscle activity responses between two different pipette models

Variable	N	t	Df	p
APB, OPB	20	3,053261	19	0,0065
FPL	20	1,770951	19	0,0926
APL, EPB	20	-0,012442	19	0,9902
EPL	20	0,818893	19	0,4230
BRACH	20	0,346934	19	0,7325

Appendix L: Mean (standard deviation, and coefficient of variation) muscle activity responses between two different pipette models. Muscles include Opponens Pollicis (OPP), Abductor Pollicis Brevis (APB), Flexor Pollicis Longus (FPL), Extensor Pollicis Brevis (EPB), Abductor Pollicis Longus (APL), and Brachioradialis (BRACH). Results presented as Mean ± SD (CV).

Muscle	***Lasec***	***Vista***	***P-value***
APB, OPP	20,76 ± 8,01% (38,58%)	15,22 ± 5,85% (38,44%)	0,0065
FPL	28,40 ± 12,99% (45,73%)	25,48 ± 12,00% (47,09%)	0,0926
APL, EPB	21,80 ± 15,17% (69,57%)	21,83 ± 13,22% (60,55%)	0,990
EPL	25,65 ± 14,00 % (54,57%)	23,26 ± 15,41% (66,25%)	0,423
BRACH	3,45 ± 2,01% (58,17%)	3,38 ± 2,19% (64,85%)	0,732

Appendix M: Paired t-test results of wrist sagittal plane and frontal plane ROM between two different pipette models.

Variable	Mean Lasec	Mean Vista	Std.Dv. Lasec	Std.Dv. Vista	N	T	df	P
Sagittal plane ROM	30,75	30,79	10,79	14,06	20	-0,012225	19	0,9904
Frontal plane ROM	44,30	46,99	13,52	15,50	20	-0,768256	19	0,4518

Appendix N: Paired t-test results of wrist postures between two different pipette models

Variable	N	T	df	P
Radial deviation	20	-2,42786	19	0,0253
Ulnar deviation	20	-2,43405	19	0,02496
Wrist extension	20	-1,99217	19	0,0609
Wrist flexion	20	-2,64936	19	0,0158

Appendix O: Mean (standard deviation, and coefficient of variation) wrist joint responses between the Lasec and Vista pipette models. P-values are also displayed. Results presented as Mean ± SD (CV%).

Position	Lasec	Vista	p-value
Radial deviation	14,04 ± 8,42° (60,01%)	5,22 ± 18,82° (360,53%)	0,025293
Ulnar deviation	16,72 ± 11,61° (69,43%)	25,57 ± 15,37° (60,11%)	0,024968
Flexion	16,63 ± 21,74° (130,75%)	31,60 ± 21,35° (67,58%)	0,015823
Extension	27,67 ± 16,58° (59,91%)	15,39 ± 23,51° (152,74%)	

Appendix P: Paired t-test results of time to task completion for traditional and ergonomically pipette models during the performance of pipetting tasks.

Variable	N	t	Df	P
Lasec Time	20			
Vista Time	20	1,055997	19	0,3042

Appendix Q: Wilcoxon Matched Pairs test results of RPE responses at the level of the hand, thumb, wrist, and forearm, for two different pipette models. Marked tests are significant at p< 0,05.

Pair of variables	Valid N	T	Z	p-value
Lasec RPE hand & Vista RPE hand	16	15,50	2,714710	0,00663
Lasec RPE wrist & Vista RPE wrist	18	29	2,460595	0,01387
Lasec RPE thumb & Vista RPE thumb	17	15	2,911294	0,0036
Lasec RPE forearm & Vista RPE forearm	18	5,50	3,484028	0,000494

Appendix R: Mean Ratings of perceived Exertion (RPE) responses at the level of the hand, wrist, thumb, and forearm of two different pipette models. p-values for each body regions were also displayed. RPE results presented as Mean RPE ± SD (CV%). Significantly different results were indicated in red.

Body regions	**Lasec RPE**	**Vista RPE**	**p-value**
Hand	10,75 ± 2,84 (26,46%)	8,8 ± 2,42 (27,49%)	0,00663
Wrist	10,2 ± 2,84 (27,84%)	8,4 ± 3,33 (39,65%)	0,0139
Thumb	12,2 ± 3,00 (24,59%)	9,5 ± 3,33 (35,08%)	0,0036
Forearm	11,4 ± 3,60 (31,61%)	8,25 ± 2,63 (31,92%)	0,000494

Appendix S: Wilcoxon Matched Pairs test results of questionnaire responses for two different pipette models.

Pair of variables	Valid N	T	Z	p-value
Lasec Q1 & Vista Q1 (Pipette grip)	15	11	2,783013	0,00539
Lasec Q2 & Vista Q2 (Task performance)	17	20	2,674603	0,00748
Lasec Q3 & Vista Q3 (Location of plunger)	15	2,5	3,265781	0,001092
Lasec Q4 & Vista Q4 (Tip application)	16	11,5	2,921545	0,003483
Lasec Q5 & Vista Q5 (Location of ejection button)	12	10,5	2,235724	0,025371
Lasec Q6 & Vista Q6 (Tip ejection)	13	0	3,179797	0,001474
Lasec Q7 & Vista Q7 (Thumb force for plunger manipulation)	18	4,5	3,527579	0,000419
Lasec Q8 & Vista Q8 (Overall fit in hand)	15	29	1,760682	0,078293
Lasec Q9 & Vista Q9 (Weight in hand)	14	48	0,282494	0,777565
Lasec Q10 & Vista Q10 (Overall comfort and efficiency)	17	5,5	3,361006	0,000777

Appendix T: Mean (standard deviation, and coefficient of variation) comfort responses of the features of two different pipette models. P-values indicate difference between models.

Pipette features	Lasec	Vista	p-value
Pipette grip	3,75 ± 1,02 (27,19%)	4,65 ± 0,81 (17,48%)	0,00538
Pipetting task	3,50± 0,95 (27,03%)	4,40 ± 0,75 (17,13%)	0,00748
Location of plunger	2,85 ± 1,31 (45,93%)	4,40 ± 0,60 (13,60%)	0,00109
Tip application	3,05 ± 1,23 (40,47%)	4,45 ± 0,83 (18,55%)	0,00348
Location of ejection button	3,30 ± 0,92 (27,98%)	4,10 ± 0,79 (19,22%)	0,0254
Tip ejection	3,75 ± 1,07 (28,53%)	4,85 ± 0,37 (7,55%)	0,00147
Thumb force for plunger manipulation	3,00 ± 1,12 (37,46%)	4,50 ± 0,69 (15,29%)	0,000415
Fit in hand	3,80 ± 0,83 (21,93%)	4,35 ± 0,81 (18,68%)	
Weight in hand	4,30 ± 0,73 (17,04%)	4,35 ± 0,88 (20,12%)	
Comfort and efficiency	3,35 ± 0,67 (20,02%)	4,50 ± 0,61 (13,49%)	0,000777

Appendix U: Comments and remarks on pipette models

Similar and repeated comments were displayed by an Asterix and the number of people who made the given comment.

Categories	Comments	
	Traditional pipette model (Lasec)	**Ergonomic pipette model**
Ease of use and preference	Familiarity makes it easier to use (2*) Preferred due to familiarity and frequent use	Unfamiliarity makes it difficult to use More time needed to familiarize themselves with pipette model (2*) Unfamiliar, need more time to practise and adjust to pipette
Plunger comfort	Not like other traditional models they use, plunger easier to depress Plunger too high, thumb extended too much for plunger operation (2*)	Plunger not too high, thumb doesn't have to extend that much
Ejection button	Ejection button a bit awkward	Position of ejection button makes it hard to operate and eject the tip, as thumb awkwardly extends to the front of the pipette
Force for tip insertion	Force required to insert tip is too much, it's difficult to insert a tip (3*)	Audible “click” feedback helpful to know when tip is secured onto the pipette shaft
Handle and shaft size, width, position, and length	Size of pipette handle accommodates any sized hand. Body of pipette too long Pipette body too long, results in shoulder being elevated throughout tasks	Location of pipette shaft being short is helpful. Doesn't cater for all hand sizes, users with small hands might struggle with operating the pipette. A bit heavy and handle too thick. Size of pipette handle/body increases the distance to reach for ejection button. Because of the way the pipette is held during pipetting tasks, wrist gets strained. Short body of pipette makes it easier to work closer to the workbench as hands wrap around the pipette
Finger hook	Stationary finger hook restricts movement, forced to hold it one way	Like adjustable finger hook because it provides options on how to hold it depending on preference and comfort

		Adjustable hook helps with grip and stabilization
Task performance	Pace is irregular when pipetting with traditional model Easy to lose focus and make mistakes, can't multitask when using it Takes more time to complete pipetting tasks	Helps maintain consistent eye focus Uniform/consistent workflow using pipette, even consistent thumb movements
Overall perception	Not a fan, forced to use it because it's the only one available in labs "This is all I know, so of course I like it	Love everything about it "It's amazing, need it in my lab" "I'm a scientist, not a fan of change"

Categories	Traditional pipette model (Lasec)
Ease of use and preference	Familiarity makes it easier to use Familiarity makes it easier to use Preferred due to familiarity and frequent use
Plunger comfort	Not like other traditional models they use, plunger eas Plunger too high, thumb extended too much for plunge Plunger too high, thumb extended too much for plunge
Ejection button	Ejection button a bit awkward
Force for tip insertion	High exertion/ force required to operate, especially wh Force required to insert tip is too much, it's difficult to i
Handle and shaft size, width,position, and length	Size of pipette handle accomodates any sized hand Body of pipette too long Pipette body too long, results in shoulder being elevat tasks
Fingerhook	Stationary fingerhook restricts movement, forced to h
Task performance	Pace is irregular when pipetting with traditional model Easy to lose focus and make mistakes, can't multitask Takes more time to complete pipetting tasks
Overall	Not a fan, forced to use it because it's the only one av "This is all I know, so of course I like it

Appendix V: Detailed table of correlations between hand anthropometric data with hand anthropometric data. Correlation coefficients (r- values) p-values displayed.

Significant results are displayed in red.

Variable	Correlations (Anthropometric data with anthropometric data) Marked correlations are significant at p < .05000 N=20 (Casewise deletion of missing data)					
	Hand Length	Palm Length	Hand Width	Palm Circumference	Thumb Length	Hand Thickness
Hand Length	1.0000 p= ---	.6464 p=.002	.6209 p=.003	.5908 p=.006	.7488 p=.000	.7519 p=.000
Palm Length		1.0000 p= ---	.7494 p=.000	.6474 p=.002	.5234 p=.018	.6107 p=.004
Hand Width			1.0000 p= ---	.7572 p=.000	.5338 p=.015	.7766 p=.000

Palm Circumference				1.0000 p= ---	.5613 p=.010	.7259 p=.000
Thumb Length					1.0000 p= ---	.7807 p=.000
Hand Thickness						1.0000 p= ---

Appendix W: Detailed table of correlations between hand anthropometric measures and Ratings of Perceived Exertion responses of two different pipette models. Table indicates correlation coefficients (r-values) and p-values.

Variable	Correlations (Anthropometric and RPE) Marked correlations are significant at p < .05000 N=20 (Casewise deletion of missing data)							
	Lasec RPE Hand	Lasec RPE Wrist	Lasec RPE Thumb	Lasec RPE Forearm	Vista RPE Hand	Vista RPE Wrist	Vista RPE Thumb	Vista RPE Forearm
Hand Length	.0929 p=.697	.0617 p=.796	.2620 p=.265	.0723 p=.762	.1367 p=.566	.0872 p=.715	.4021 p=.079	-.1137 p=.633
Palm Length	.1061 p=.656	-.0610 p=.798	.1670 p=.482	-.0076 p=.975	-.0132 p=.956	-.1437 p=.546	.2236 p=.343	-.0766 p=.748
Hand Width	.0235 p=.922	-.0574 p=.810	-.0455 p=.849	.1771 p=.455	.1127 p=.636	.0855 p=.720	.2796 p=.232	-.0210 p=.930
Palm Circumference	.1915 p=.419	.1434 p=.546	.1567 p=.509	.3803 p=.098	.0708 p=.767	.0038 p=.987	.4220 p=.064	-.1315 p=.580
Thumb Length	-.0187 p=.938	-.0412 p=.863	-.0170 p=.943	.1785 p=.451	.0308 p=.897	.0218 p=.927	.3405 p=.142	.0166 p=.945
Hand Thickness	.1291 p=.588	-.0302 p=.899	.1445 p=.543	.3022 p=.195	.1491 p=.530	.1598 p=.501	.4427 p=.051	-.0376 p=.875

Appendix X: Detailed table of correlations between hand anthropometric measures and muscle activity responses of five muscles for two different pipette models. The correlation table displays correlation coefficients (r-values) and p-values.

Variable	Correlations (Anthropometric data with Muscle activity) Marked correlations are significant at p < .05000									
	Lasec OPP, APB	Lasec FPL	Lasec APL, EPB	Lasec EPL	Lasec BRACH	Vista OPP, APB	Vista FPL	Vista APL, EPB	Vista EPL	Vista BRACH
Hand Length	-.4516 p=.046	.0560 p=.815	-.1565 p=.510	-.4122 p=.071	-.5866 p=.007	-.4260 p=.061	-.2017 p=.394	-.4141 p=.070	-.3566 p=.123	-.6017 p=.005
Palm Length	-.4543 p=.044	.1011 p=.671	-.0821 p=.731	-.4239 p=.063	-.3978 p=.082	-.2114 p=.371	.1373 p=.564	-.1951 p=.410	-.2902 p=.214	-.3862 p=.093
Hand Width	-.5520 p=.012	.2618 p=.265	.2383 p=.312	-.1567 p=.509	-.4030 p=.078	-.2572 p=.274	.0802 p=.737	-.0160 p=.947	-.3286 p=.157	-.4689 p=.037
Palm Circumference	-.2205 p=.350	.1251 p=.599	.1644 p=.489	-.2977 p=.202	-.5153 p=.020	-.1821 p=.442	.0155 p=.948	-.1472 p=.536	-.3062 p=.189	-.5847 p=.007
Thumb Length	-.2498 p=.288	.0048 p=.984	-.3497 p=.131	-.4489 p=.047	-.5055 p=.023	-.5393 p=.014	-.1376 p=.563	-.5150 p=.020	-.3316 p=.153	-.4921 p=.028
Hand Thickness	-.4342 p=.056	.2016 p=.394	-.2420 p=.304	-.3398 p=.143	-.6706 p=.001	-.3328 p=.152	.0726 p=.761	-.5227 p=.018	-.5033 p=.024	-.6880 p=.001

Appendix Y: Detailed table of correlations of anthropometric data with questionnaire responses of two different pipette models. Correlation coefficients (r-values) and p-values are displayed.

		Correlations (anthropometric data and questionnaire responses) Marked correlations are significant at p < ,05000 N=20 (Casewise deletion of missing data)					
Variable		Hand length	Palm length	Hand Width	Palm circumference	Thumb length	Hand thickness
Lasec	Q1	-,2616 p=,265	-,4638 p=,039	-,1517 p=,523	-,0979 p=,681	-,0428 p=,858	-,2055 p=,385
	Q2	-,0821 p=,731	,1084 p=,649	,3550 p=,125	,1092 p=,647	,2319 p=,325	,1631 p=,492
	Q3	-,5922 p=,006	-,5719 p=,008	-,4046 p=,077	-,3332 p=,151	-,2564 p=,275	-,2928 p=,210
	Q4	-,0801 p=,737	,2538 p=,280	,2032 p=,390	,2442 p=,299	,0002 p=,999	,1415 p=,552
	Q5	-,1546 p=,515	-,1752 p=,460	,0882 p=,712	-,0188 p=,937	-,0649 p=,786	,2273 p=,335
	Q6	-,2212 p=,349	-,0671 p=,779	,1061 p=,656	-,1216 p=,609	,0694 p=,771	,1583 p=,505
	Q7	-,3655 p=,113	-,1622 p=,494	-,2344 p=,320	-,1520 p=,522	-,1217 p=,609	-,3968 p=,083
	Q8	-,1923 p=,417	-,1367 p=,566	,0278 p=,907	,0535 p=,823	-,0634 p=,791	-,0257 p=,914
	Q9	-,2905 p=,214	-,2395 p=,309	-,1487 p=,531	-,2793 p=,233	-,1204 p=,613	-,2718 p=,246
	Q10	-,2184 p=,355	,1036 p=,664	,0262 p=,913	-,0692 p=,772	-,0890 p=,709	,0135 p=,955
Vista	Q1	,0324 p=,892	-,2538 p=,280	-,1096 p=,646	-,0344 p=,886	,0676 p=,777	,0879 p=,713
	Q2	-,0399 p=,867	,0786 p=,742	-,0357 p=,881	-,0709 p=,767	-,0163 p=,946	,0480 p=,841
	Q3	-,2009 p=,396	-,1752 p=,460	-,2112 p=,371	-,0203 p=,932	,0662 p=,781	-,2253 p=,340
	Q4	-,1502 p=,527	-,1891 p=,425	,0313 p=,896	-,3735 p=,105	,0311 p=,896	,1092 p=,647
	Q5	-,3972 p=,083	-,1533 p=,519	-,5911 p=,006	-,4862 p=,030	-,2508 p=,286	-,6075 p=,004
	Q6	,2222 p=,346	,2457 p=,296	,0607 p=,799	,0425 p=,859	,3458 p=,135	,0247 p=,918
	Q7	-,0255 p=,915	-,1291 p=,587	,0000 p=1,00	,1621 p=,495	,1200 p=,614	,0244 p=,919
	Q8	,1525 p=,521	-,0042 p=,986	-,1429 p=,548	,0717 p=,764	,2226 p=,346	,2092 p=,376
	Q9	-,0816 p=,732	-,2070 p=,381	-,4791 p=,033	-,2010 p=,396	-,0197 p=,934	-,3038 p=,193
	Q10	-,0289 p=,904	,2591 p=,270	,2663 p=,256	,2337 p=,321	,1749 p=,461	,1215 p=,610

Appendix Z – Maximal Voluntary Exertion movements adapted from Kendall et al., (2005).

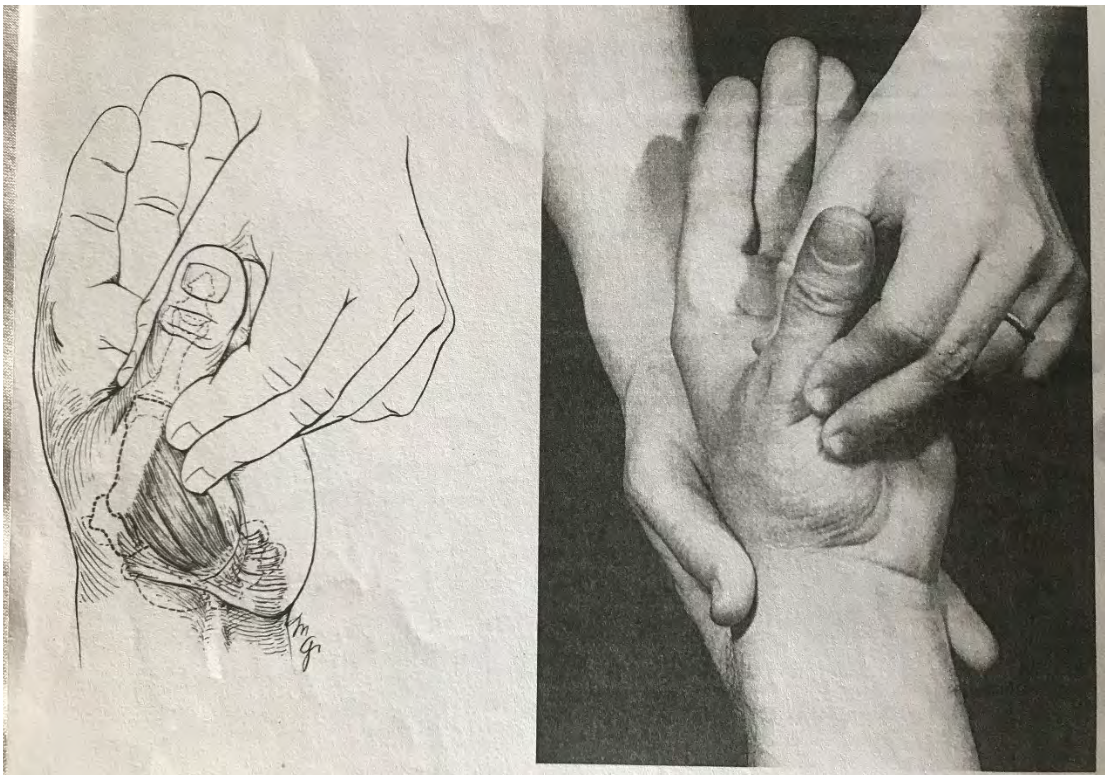

Figure 27: Opponens Pollicis

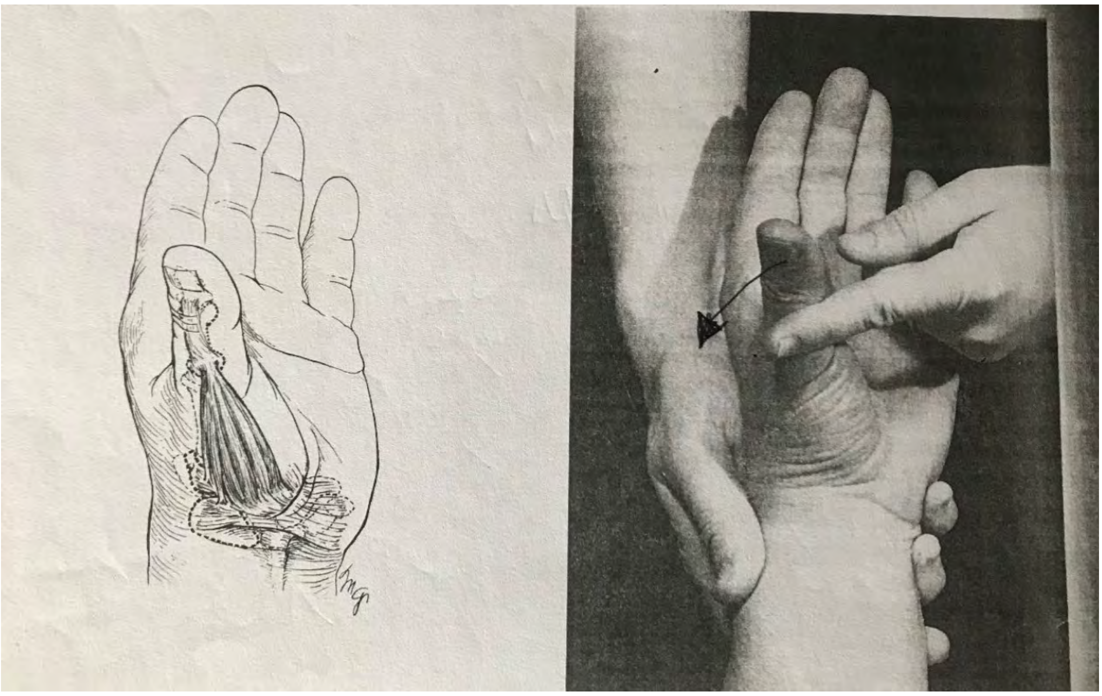

Figure 28: Abductor pollicis Brevis

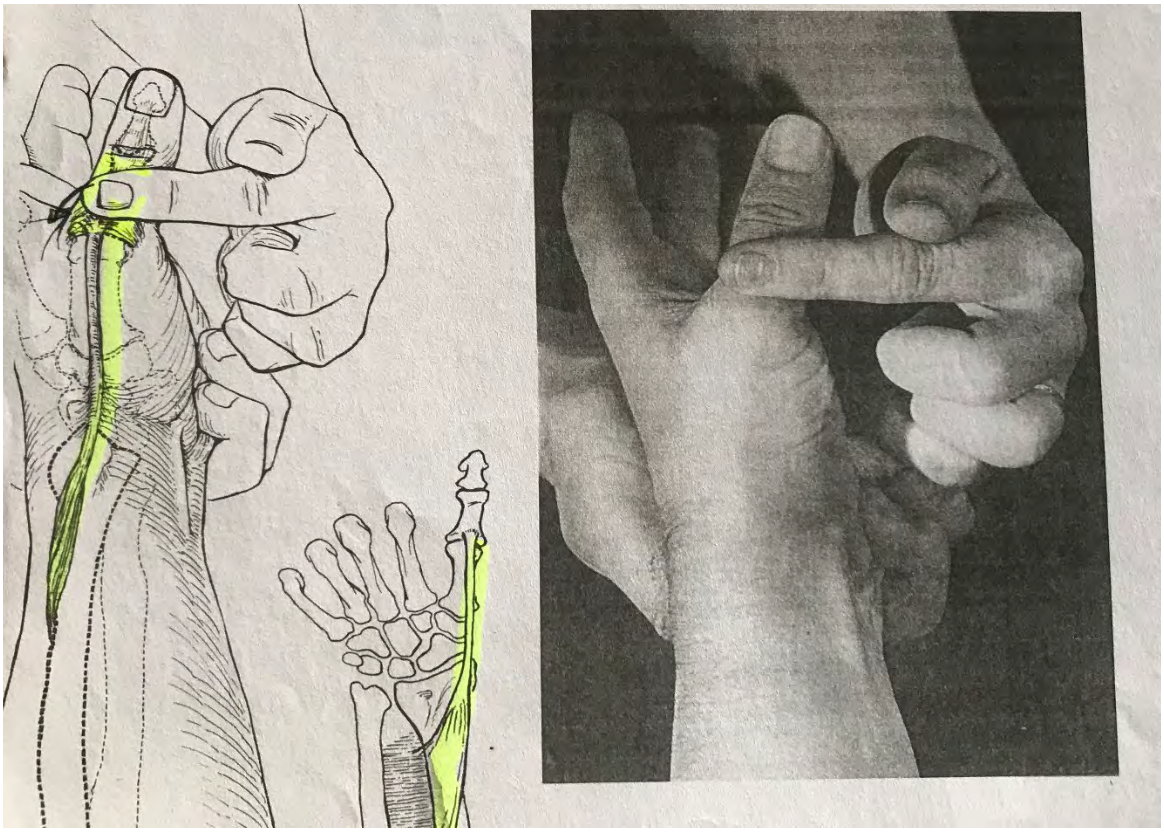

Figure 29: Extensor Pollicis Brevis

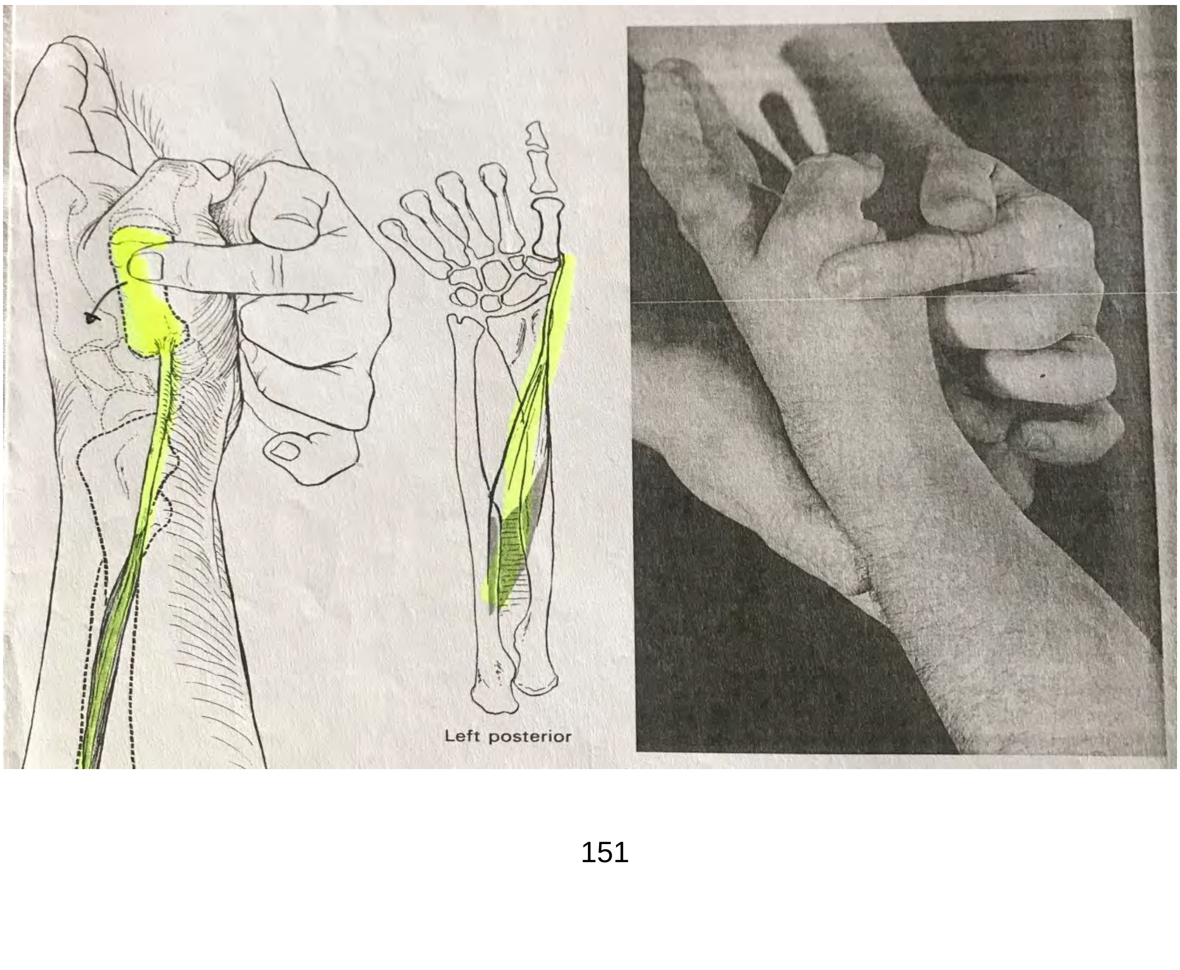

Figure 30: Abductor Pollicis Longus

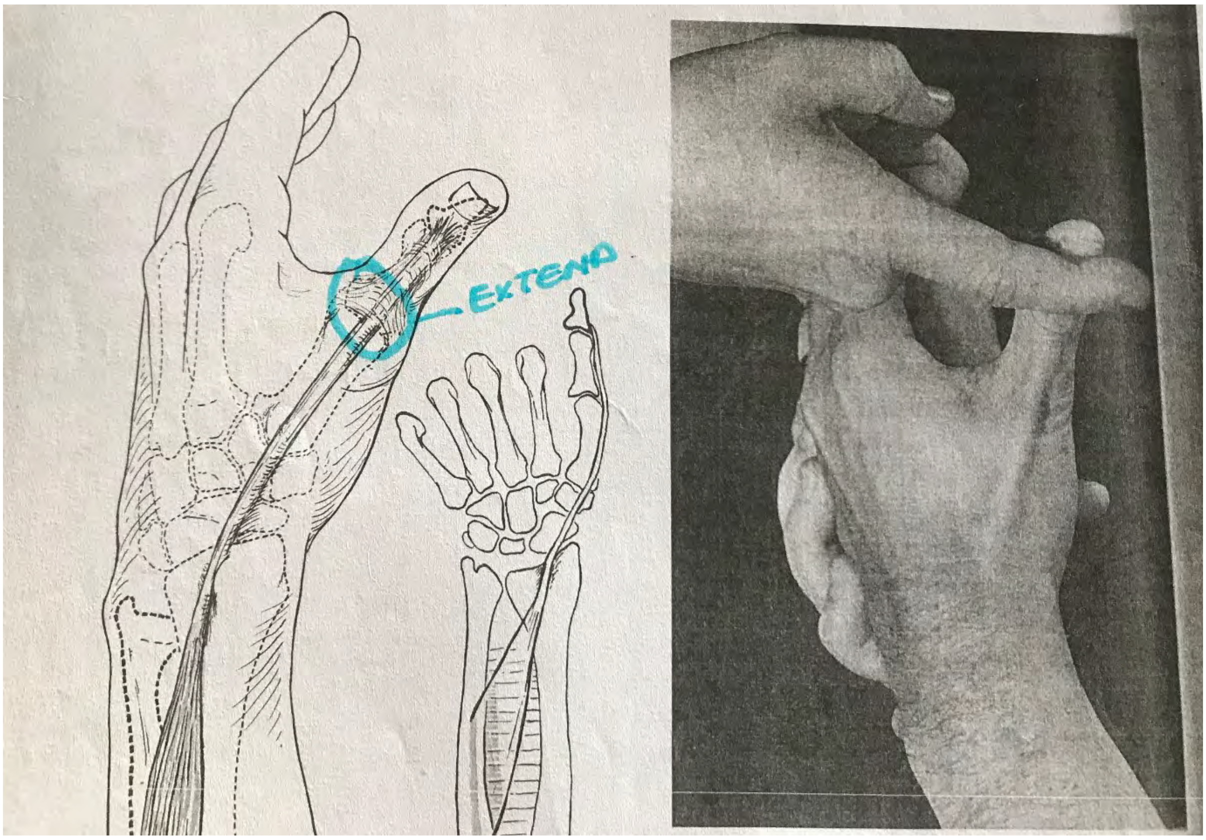

Figure 31: Extensor Pollicis Longus

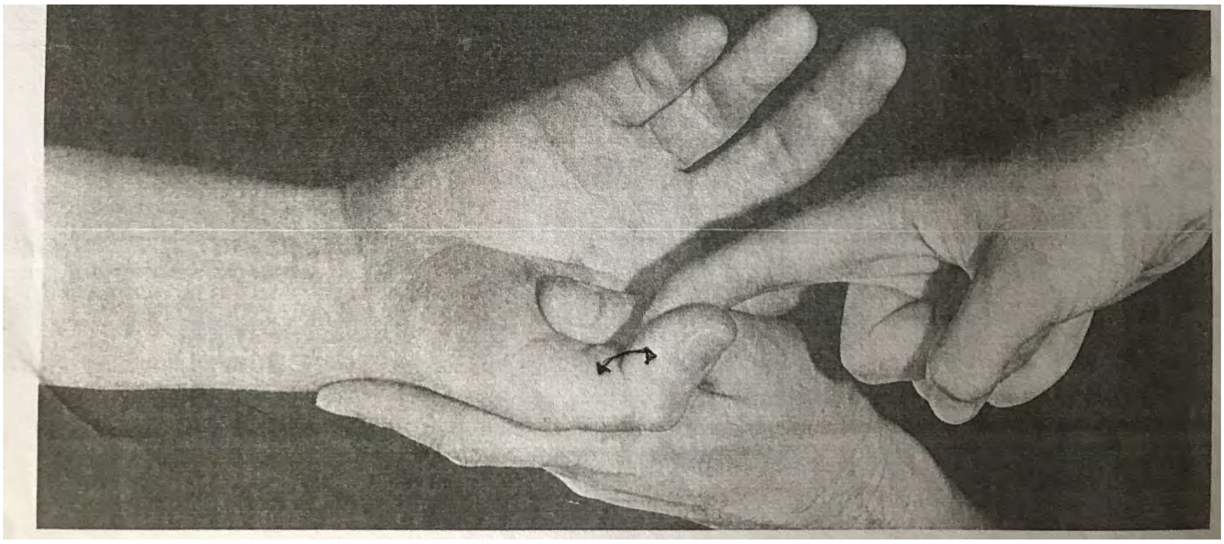

Figure 32: Flexor Pollicis Longus

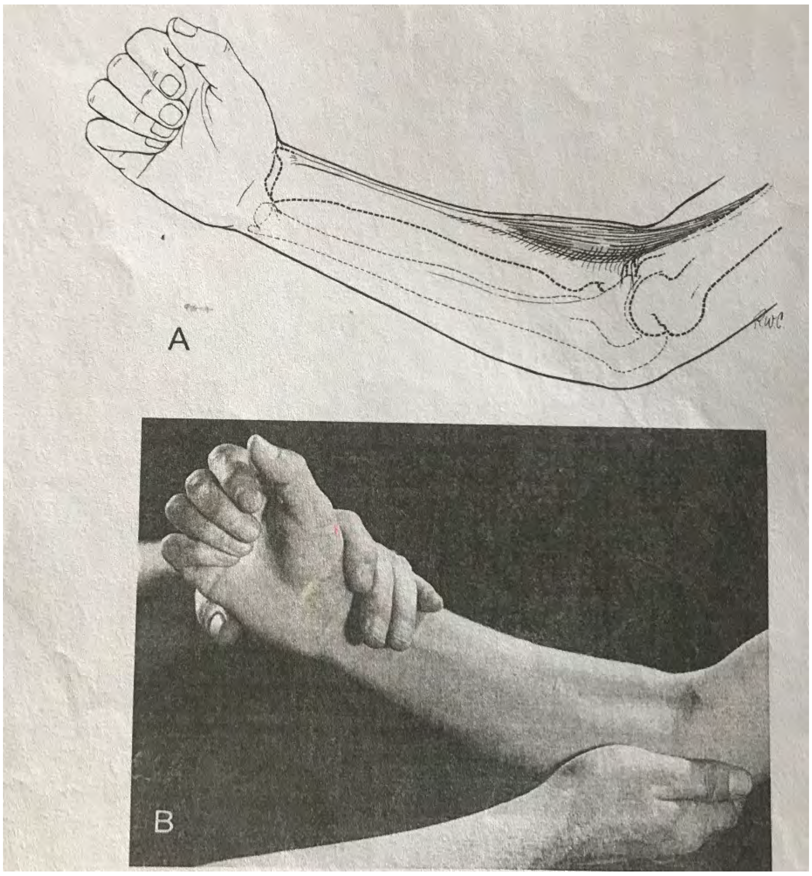

Figure 33: Brachioradialis