Aircraft Cockpit Accommodation: A Pilot Study

by

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Abstract

Anthropometric measures are the cause of the majority of pilot rejection from the Royal Canadian Air Force (RACF). Though the fit mapping procedure is rigorous, it is not free from error. The purpose of the study was to test a novel method intended to automate a more rigorous set of testing procedures to predict pilot suitability to a higher degree using reach trials and anthropometric measurements. Anthropometric measurements were taken, and participants performed several reaching tasks in a mock-up of a cockpit. The Certus Optotrak was used to determine reach distances by calculating the distance between a virtual point located on the hand to IRED sensors affixed to the arm of the participant. Partial Least Squares was used to develop regression models with validation to not only predict reach distances of participants, but to predict reach performance. Reach performance calculated at 94% using contingency tables, showing the validity of this method for future use.

Acknowledgements

Bruce Lee once said, “Patience is not passive, on the contrary, it is concentrated strength.” If that is true, I would like to thank Dr. John Kozey for being the strongest man in the world. I was lucky to stumble into this project and even luckier to have stumbled into working with you. The experiences and opportunities you have given me will stay with me for the rest of my life. Absolutely none of this would have been possible without you. Thank you. To my committee members Dr. Heather Neyedli and Dr. Michel Ladouceur, whose expertise has been invaluable, thank you. You have been no less patient. Dr. Sasho MacKenzie, my external examiner, thank you for giving me your time and feedback.

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Chapter 1: Introduction

The increasingly complex nature of today's military aircraft demands more extensive and expensive training for pilots (DeCarlo, 2014), therefore it is important to have effective pilot selection processes. In addition to operational and knowledge-based decisions, it is important to match physical human characteristics (anthropometrics) with the workspace of the aircraft understanding that each aircraft has its own unique workspace. The Royal Canadian Air Force (RCAF) has identified the major physical limitations to recruits who wish to be pilots are physical space and reach, which are significant determinants of a pilot's suitability for aircraft selection. Screening procedures have been developed to alleviate the costly mismatches of the pilots and aircraft in the RCAF, however, in some cases, the procedures have proven to be unsatisfactory and are in need of review.

Anthropometric dimensions are collected from individuals to verify whether a candidate's physical size will be a limitation. The existing screening procedures of anthropometric dimensions of recruits, include principal component analysis (PCA), multiple linear regression modelling, and fit mapping. PCA is a dimensionality reduction method, that transforms data sets with a large set of variables to fewer variables (reduced dimensionality) while retaining most of the important information in the original data. Multivariate regression, an alternative to PCA, encompasses simultaneous observation and analysis of more than one variable. It helps to understand the relationships among variables in the dataset and helps understanding the correlation between dependent and independent variables. Fit mapping or physical assessment is a process in which statistical models for aircraft cockpit accommodation are derived and used to determine suitability of pilot when screening procedures do not produce definite results. Test participants (dressed in full flight gear – helmet, life support equipment, flight suit, winter, or immersion garments) are assessed on their ability to achieve the necessary performance on all test criterions within a physical mock-up of the cockpit. Adjustable seat positions are noted if they are required to accommodate the various positions. Reach data and the visual angle achieved are based on multiple regression models based on measures of performance, seat positions, and anthropometry. Alternatively, others can be based on threshold limits such as maximum seated height (Crawford, 2000; Zehner, 2002).

Specific anthropometric measurements have been deemed the most important for accommodation testing in cockpit design. These measurements were determined through ergonomic research focusing on anthropometric accommodation of aircraft cockpits, and are listed below in Table 1 (Joslin, 2014; Kennedy, 2001; Massenburg, 2006; Zehner, 2001). Using these dimensions to determine suitability became the next challenge in determining suitability for “fit”.

Table 1. Physical requirements and their corresponding anthropometric measurements.

Requirement	Corresponding Anthropometric Measure(s)
Overhead clearance	Seated height
Rudder pedal operations	Thigh length, leg length
Internal/External visual fields	Seated eye height
Knee, leg, & torso clearance of cockpit structures	Seated knee height, buttock – knee length
Leg clearance of main instrument panel	Seated knee height, buttock – knee length
Leg clearance of control stick	Thigh length
Hand reach to controls / thumb tip reach	Acromion to tip of distal phalanx of third finger

Despite the rigorousness of measurement taking processes as well as methods of statistical model creation, the system is not ideal. The process by which anthropometric standards for a given aircraft are developed is based on the methodology described by Hudson et al and employed in the United states air force (Keefe, 2017). Zehner et al. (2002) showed that with the current methodology, depending on the aircraft, accommodation rates can be as low as 27.4% for small female pilots, and 79.7% for large male pilots due to various anthropometric constraints.

Of the measurements recorded, excessive femur length, reach envelope and having a seated height exceeding the maximum cut off for the cockpit were among the most prominent causes of mis-match (Keefe, Angel, & Mangan, 2012).

Variability in size, posture and helmet fit between different pilots complicates the ability to determine a precise cut off for seated height requirements in cockpit accommodation. It was found when graphing the data, that not all points fall on a straight line, which indicates variability within the measurements as shown in Figure 1. While pass/fail limits are still rigid, there is a grey area which complicates matters. If a participant measures close to the upper limit of a pass condition, it is recommended they be tried for “in cockpit verification”. As well, it is not sufficient that a pilot be able to pass all conditions, they must be able to do so using only one seat position (Keefe et al., 2012). This means that it is unreasonable to assume that a pilot should need to adjust the seat position in accordance to the specific task he or she is attempting to complete. By creating models based on anthropometric dimensions that predict reach, the amount of fit-mapping required can be reduced, saving time and money.

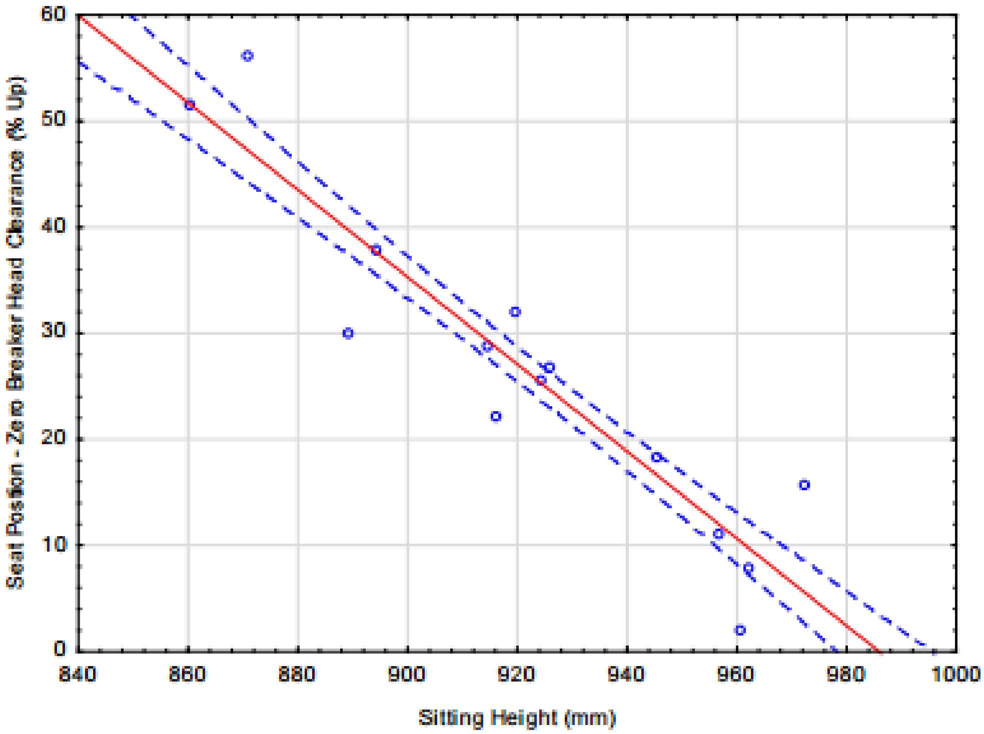

Figure 1 Seat position at zero clearance to ejection seat canopy breakers (Keefe et al., 2012).

The objective of this study is to demonstrate a proof of concept of what sort of model/technique is best to assess a pilot's physical accommodation within an aircraft cockpit as well as evaluate the aircrew candidate's suitability for fit within an aircraft. This was done using a technique similar to that of Zehner et al. (2002), where the fixed distance was measured from the radial stylus, and was unique to every pilot. In this case, the reach results are measured along with the span of the participant at once. By using specific anthropometric dimensions, regression models were made to predict reach. Success of the approach will be determined if the models lead to an accuracy of more than the previously reported 80% (Zehner, 2002). If successful, this methodology will also be suited to various workstation designs in several other industries as well as other vehicles or machinery.

The participants will reach to several targets with their right arm. The difference in the distance between the participants reach and the target location was measured using 3-D motion capture. Multiple linear regression was used to derive regression equation(s) to predict the reach distance of a participant based on the anthropometric dimensions.

This study is a proof of concept from which Defence Research and Development Canada (DRDC) can attempt to determine the viability of developing a measurement process for pilot selection. As such, the proposed methods were derived by DRDC for their specific use case.

1.2 Purpose

The purpose of this pilot study is to develop novel methodology to predict reach distance and performance in a simulated cockpit using 3-D motion capture and a statistical based approach using multiple linear regression.

1.3 Hypothesis

It is hypothesized that multiple linear regression equations based on selected anthropometric dimensions of associated reach and visual measures will provide an accurate model of human reach.

Hypothesis 1: Maximum reach distances can be accurately modeled from structural anthropometric dimensions.

Hypothesis 2: Maximum reach performance can be accurately estimated from statistical reach models.

Chapter 2: Review of Literature

Ergonomics seeks to fit the job to the person, thus, requiring a variety of static and dynamic anthropometric measures to create balanced designs. These are to ensure a minimization of harmful postures and stresses to due improper design (B. Das & Sengupta, 1996; Konz & Johnson, 2008). However, despite the effort that goes in to ensuring proper ergonomics and human factors research, providing a “good” human-system interface is not always seen as “added value” to a product from a manufacturer’s perspective. On the other hand, poor application of ergonomic principles or a failure to provide a user-friendly interface merely detracts from its value. As such, convincing an aircraft manufacturer to invest in human factors research is sometimes a difficult argument. Many times, there are competing constraints and decisions are made as trade-offs between competing constraints. Most current interfaces are seen as adequate and minor deficiencies become a training or selection issue to be dealt with within the purchaser’s organization rather than being the manufacturer’s problem (Harris, 2007). This is an issue with military aircraft because the personnel must be able to use the provided equipment in complex, highly stressful situations. Adding human factors to the design phase of a product can bring about performance enhancing benefits and reduce operational and life costs. When viewed in this light, it can now be seen to “add value” (Harris, 2007).

Estimations put the price of training a pilot at 1 million dollars (Cdn.) and retraining that pilot for aircraft reassignment, 3 million dollars. Pilots are placed in training pipelines based on anthropometry. The price comes from mistakenly training a pilot in an unsuitable pipeline, retraining in a suitable pipeline and then training another to replace them in the original pipeline (Tucker & Brattin, 2000). Due to the high price of purchasing aircraft, and training crew, it is no wonder that proper human factors and ergonomics is considered of great importance. To ensure pilots can successfully operate the aircraft, they must meet various accommodation requirements and this should be conducted before the training is commenced.

2.1 Design

Even the smallest changes in design have been shown to have an impact on productivity of the individual and health and safety, showing that the ergonomic approach that considers anthropometry can pay off in the long run for the employer (Biman Das & Grady, 1983). There remains an issue for legacy equipment and modernization in contrast to changing demographics of personnel. For example, the United States Navy re-evaluated all equipment in 2006 and coded the anthropometric information in a database. In consideration of the anthropometric measurements of existing crew, it has been mandated that no modifications to existing or legacy equipment will either hinder or reduce existing accommodation without justification. Future designs will aim to accommodate a greater proportion of the user population that will be using them (Massenburg, 2006).

When designing for a cockpit or other workstations that account for multiple factors aside from reach envelope, the whole body must be considered when implementing design changes. Even muscle strength should be considered when designing based on anthropometry when force application is a prime factor to consider when designing workspaces. Simply reaching the control is not sufficient, an individual must also be able to operate or manipulate it effectively. The tasks required of the individual will determine which anthropometric dimensions must be considered and should extend beyond the notion of average since no one is average in all dimensions (Daniels, 1952; Hertzberg, 1960).

In addition to the tasks required, another aspect that needs to be identified is the intended function of the workspace. Individuals will adopt various postures and limb positions while completing the task and these behaviours must also be noted (Hegde, 2013). Posture, foot base, type of grip, weight in hands, and proximity to obstacles in the area are a few notable factors. Many of these variables solely consider the upper body, however floor based controls such as pedals, will require the reach envelope of the lower body to be considered in the design as well (Konz & Johnson, 2008).

Limiting tasks to the normal work area, defined as the area covered by the forearm as it moves from side to side in front of the body, has been shown to greatly reduce the risk of musculoskeletal injury for a worker. It is important to consider comparing the low and high frequency of body movements required when designing work spaces (Konz & Johnson, 2008). General design considerations include the importance, frequency, function, and sequence of the operation to the overall goals of the task as critical factors in the design.

To do this, it is important to be able to differentiate the limits of each arm, as well as where they overlap, known as zone differentiation. When displaying reach envelopes, this method helps determine the limits of each limb (J. J. Yang & Abdel-Malek, 2009). Objective functions, which are human performance measures, are what govern human motion. They are often combined into what are called cost functions, which repersent the postures adopted for movements that involve multiple obejective functions. The cost function values are evaluated by dividing the workspace into several small zones, and a different colour is assigned for each. Once completed, the painted zones are visualized (J. Yang, Sinokrot, Abdel-Malek, Beck, & Nebel, 2008).

Cockpit design has many important factors, one being exterior vision. Placement of instruments, controls and displays should obscure as little of the exterior view as possible while remaining accessible. In order to accomplish this, a pilot's sight lines as well as working ranges and evaluations of the pilot's body are required. However, each cockpit design will be different and may require different body measurements. For example, a seat that slants back will emphasize the height from the buttocks to the position of the eyes as well as the buttocks to the patellae (Guoying, 1991).

Using a hierarchical cluster approach, Zhang, Sun and Chen (2014) determined the ergonomic design elements required when developing a transport category airplane. Figure 2 shows the design elements and their relationships to one another. In their approach the key components of design are mapped out against the different phases of the design and production process. Front loading the application of ergonomic principles will reduce the overall cost of the design and production process.

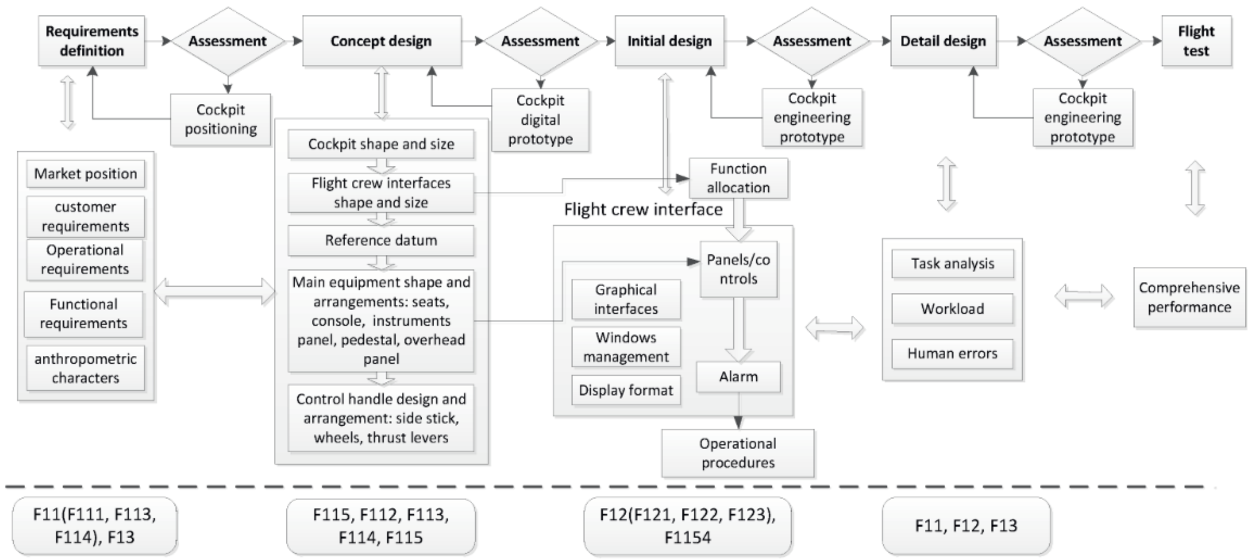

Figure 2 The relationships of the ergonomic design elements of transport aircraft cockpits (Zhang, Sun, & Chen, 2014)

Determining the level of accommodation of a workstation is accomplished by summation of various measurements which deal with the extreme ends of the spectrum also known as an anthropometric fit test (Bradtmiller, 2015). Tucker and Brattin (2000) found that large individuals must meet a limited combination of sitting eye height and buttock to knee length to ensure there is a seat location that provides overhead clearance and knee clearance to the instrument panel. Shorter individuals likewise must meet a limited combination of sitting eye height and thumb tip measurements to ensure reachability of controls and sight over the nose of the aircraft. The measurements were based on previous guidance and regression equations from UN/USMC cockpit accommodation evaluations (Tucker & Brattin, 2000).

Ideally, an anthropometric fit test is conducted during the design phase of a product, with the first step being to identify the target user with a sample size representative of the population. Next, anthropometric measures of the target population are needed and taken into consideration for the evaluation of fit. Lastly, statistical techniques are used to analyze the data to determine if the product meets the required criteria. Through these statistical techniques the proportion of the target population that will be accommodated can be determined (Bradtmiller, 2015).

2.2 Anthropometric Measures

It is a misconception that there is an average person when it comes implementing design for a large population. One person may be considered average in several measurements yet not in others. It was shown using 4064 aircraft personnel, even when the average was defined as a tolerance value (mean $\pm$ 15%), none of the participants were considered average in even ten of the dimensions. (Hertzberg, 1960) This leads us to question how one is meant to compile applicable data of anthropometric measures, considering most of the dimensions are not all linearly correlated (Roebuck, 1995).

Multiple guidelines exist to help facilitate the collection of static anthropometry data which covers the efficient setting up of collection spaces, palpitation of landmarks, order in which the data should be collected, communication between the researcher and the participant to best report the findings (Centres for Disease Control and Prevention, 2007). Although there will be variations in the findings depending on the intended use, it is reasonable to follow these guidelines in order to most effectively conduct an anthropometric survey (Kamal, 2006; Roebuck, 1995).

Anthropometry however, is more challenging than a simple univariate measurement for the length of a limb. Often, links, which are the segments between joints, are made up of several bones, ligaments, muscles, and other surrounding tissues, alter how limb lengths are measured based on different reach targets. It is very important to make sure that joint centres are identified accurately in order to collect valid data.

2.3 Databases

There are numerous databases from which structural measurements could be drawn. For instance, in 2012, the Canadian Armed Forces conducted a research study to improve the accuracy of supplied clothing and uniforms, in which anthropometric measurements of 2200 military personnel were compiled and analyzed. The aim was to improve on the standard sizing such as small, medium, large and extra-large. Along with providing information on the fit of the clothing, the measurements were also used in equipment and vehicle design to more accurately accommodate the range of body types without a sacrifice in function (Keefe et al., 2012). Additionally, every two years the Canadian Health Measures Survey (Questionnaire, 2017) is sent to Canadians with the intention of gathering health, physical, and environmental measures of the population of Canada.

Despite continued surveys, there is currently no prescribed anthropometric database for use in the Federal Aviation Regulations. Although there are bibliographies complied that reference anthropometric databases applicable to aviation design, none of them provide data sources representative of the current target population (Joslin, 2014).

While measurements exist in multiple large databases for various military personnel as well as general populations from which to obtain data, determining the way in which these measurements relate to one another is challenging. Due to the lack of a standard procedure when publishing the details of floating dimensions derived from landmarks, it is difficult to normalize data in a meaningful way. Some data is represented using a 3 dimensional coordinate system or local coordinate system on a limb to help define certain measures that may be of importance (Roebuck, 1995).

Worker requirements among various workstations are not necessarily the same as in aircraft cockpit design, however, the overall approach remains the same. Various anthropometric studies for a host of purposes can be used as source data, yet due to each case being specific, the previously derived measures prove difficult to use with any degree of certainty (B. Das & Sengupta, 1996). Because of the difficulty involved in imparting required criteria in a way that is relevant to designers, the designs of many workstations do not include these measurements (Biman Das & Grady, 1983).

When considering the control forces and body movements required in an aircraft, the industry that most closely matches is motor vehicle / tractor-cab industry. However the anthropometric databases for these industries relied on small sample sizes or gathered exclusively from their operators which were not representative of the target pilot population and therefore could not be used for aircraft design (Joslin, 2014). Due to this, legacy anthropometric measures are used and they may not be representative of target pilot populations. While legacy anthropometrics might capture structural measurements, they have not been shown to be indicative of specific functions. Testing to determine whether structure and function are linked would still be required.

Proper design requires more than simply a description of an individual’s size, position and posture while performing operations are also of importance (Roebuck, 1995). Due to the varying needs of workstations and the different specifics of each cockpit, as well as the degree of difficulty in relating previously derived measurements to new applications, it is often required to take one's own measures when creating or proposing any changes to existing designs.

Despite the many predictions of reach curves and volumes, a disconnect still exists between the application and the collection of these measurements due to the variability inherent in each individual in addition to the complex nature of defining accurate reach. Body shape and position, shoulder and elbow range of motion, types of restraints being used and of course, clothing can affect these measurements (Stoudt, 1973). Different collection procedures and methodologies will often produce different results because of the multiple factors. Suffice it to say, most applications require specific anthropometric measures that are not necessarily of use in other instances. As well, they are difficult to measure accurately making the use of previously derived measurements suspect.

Another issue with databases is there are often not sufficient anthropometric data on different populations. While North American populations, as well as Australian and Western European populations have been recorded numerous times. Central and South American, African, as well as most mid and far East populations lack sufficient data from which to draw. It is also worth noting that what anthropometric data has been collected, it was conducted on military personnel which could differ from the civilian population (Kennedy, 1976).

2.4 Differences Between Populations

There is also a degree of difficulty in designing for anthropometric measures alone as different populations tend to vary with respect to these dimensions (Lee et al., 2013).

When designing a cockpit for the middle 90% of the target population of one nation, one must be aware that these dimensions are only relevant to this specific population (Kennedy, 1976). When measuring 21 anthropometric dimensions of 94 male Korean helicopter pilots, it was found that the anthropometric dimensions of the Koreans tend to be larger than the average male Korean civilians and the measurements are less dispersed than those of the personnel in the US Army (Lee et al., 2013).

Not only does lack of appropriate accommodation produce conditions which render the aircraft uncomfortable to operate, it can be dangerous. Figure 3 indicates dimensional changes that would be required in order to accommodate a US cockpit to the Japanese or Vietnamese.

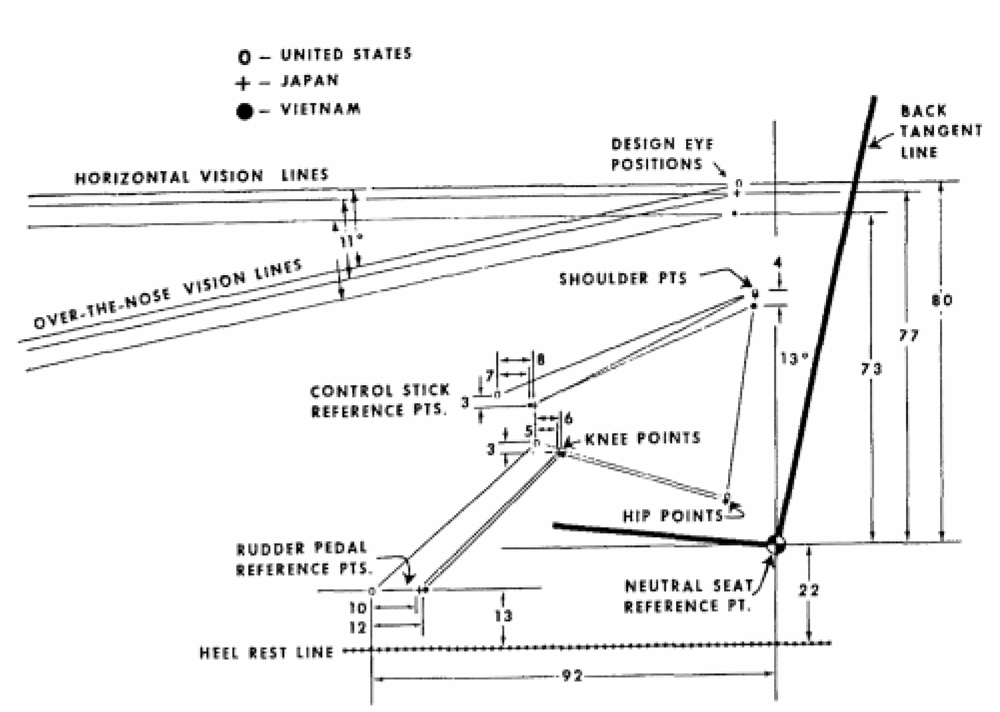

Figure 3 modifications in the basic cockpit geometry required to accommodate Japanese and Vietnamese pilots (Kennedy, 1976).

In the same vein, Figure 4 shows the difference in standing stature between seven different military populations. It is quite clear that there is a significant difference between not only ethnicities, but also between different countries.

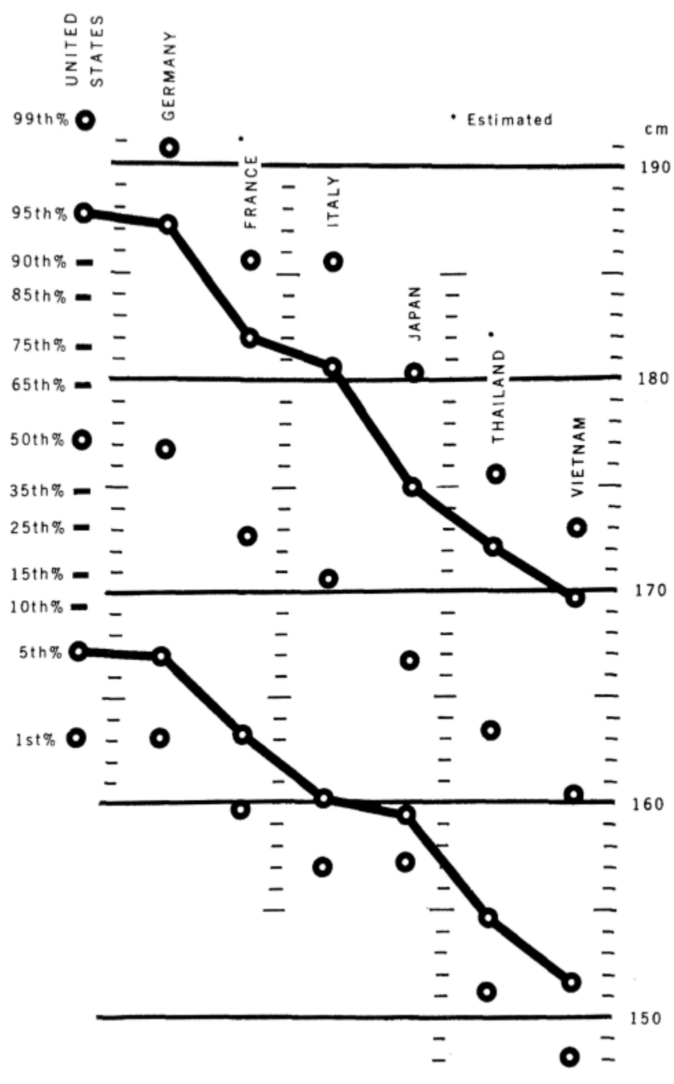

Figure 4 Variations in standing stature of the 90th percentile in 7 different military populations (Kennedy, 1976).

Even more, the degree to which anthropometry plays a role in pilot selection within a specific population shows itself in a study conducted on the Croatian Airforce. When morphological features of both cadets and pilots were compared with those of the conscripts in the Croatian Army, it was found with 86.48% accuracy that an examination of a participant could predict which of four groups they belonged (Kalebota, Drenovac, Szirovicza, & Zivicnjak, 2005).

As military procedures move to be more inclusive there are historical design issues that must be overcome regarding accommodation. Historically, military aircraft have been designed to male specifications. Since women tend to be shorter, have smaller limbs and have less upper body strength, some may not be accommodated by such systems and may experience difficulty in reaching controls and operating certain types of equipment (Weber, 1997).

The acquisition policy of the Department of Defense states that human considerations be integrated into design efforts by focussing attention on the human operator to improve system performance. Suggested guidelines state 95^{th} and 5^{th} percentile dimensions for males when designing weapons systems. While only 10 percent of men will not be accommodated in a given measure, Webber (1997) argues that many more women will not be accommodated due to the vast difference between a 5% female and a 95% male (Weber, 1997).

It has been shown that the proportion of limb length to stature are greater in men than in women, however the opposite is true of the ratio of sitting height to stature, which is often used to calculate trunk length. The buttock to knee length was also found to be greater in women because of size and shape of the buttocks (Pheasant, 1996). The proportion of fat percentage is also greater in women, which could affect reaching characteristics and impact movement (Durnin & Rahaman, 1967). More than just placing women on the left side of the bell curve of measurements, this creates a bimodal distribution which must be considered when designing for the pilot population.

Although it has been shown to be more cost effective to design to a specific subset of the population rather than expand the accommodation to allow for a greater pool of potential pilots (Şenol, 2016), this method would serve to exacerbate the existing problem rather than to alleviate it.

2.5 Reach Accommodation

Not only must we account for physical dimensions and anthropometry when designing spaces for humans, but we must be aware that there are certain measurements that cannot be predicted by a single linear dimension. Human reach is a complicated and time consuming measurement to acquire, yet understanding where, and how accurately and effectively an individual can reach is a very important measurement that allows for a more efficient design.

Much of the early work done to define reach envelope involved basing predictions of curves on measures of static anthropometry, or creating complex jigs that a subject would touch at various points in space (Faulkner & Day, 1970). In 1947, King, Morrow and Vollmer attempted to quantify the full range of reach. They enlisted 139 military subjects to sit in a pilot's seat with a lap belt, shoulder harness and cushion for the back. The subjects were asked to touch points at specific levels on a vertical rod that was attached to a horizontal support with a known relation to the seat reference position. Data was compiled and summarized into means and standard deviations for different heights and 4 arm angles. The data found that a person's reach was the greatest around shoulder height and increases as they reach laterally (Kennedy, 1964; Stoudt, 1973). Dempster was able to determine that the method employed in operating the controls could alter reach envelopes. He discovered that the grip type will change the reach and available range of motion (Biman Das & Grady, 1983; Konz & Goel, 1969).

While reach volume is correlated to static measures such as arm length, predicting the postures a person will adopt in order to perform a specific task is difficult to accomplish (Choi & Mark, 2004; Reed, Parkinson, & Klinkenberger, 2003). A study conducted to determine the effects of the interior geometry of a vehicle on the anthropometric variables of posture found that drivers were found to adapt to changes in design primarily through limb posture. Most of the variability in driving posture was explained by stature (Reed, Manary, Flannagan, & Schneider, 2000).

Upper body mobility and curvature of the spine varies depending on the postural changes adopted from seated to standing. In addition to this, the limits on the range of motion are impacted by the type of grip employed by the individual for a task (B. Das & Sengupta, 1996). If maximum reach measurements are desired, a question arises as to whether the resultant movement limited to the shoulder while the torso is kept stable, or if the total reach with the allowance of postural change takes precedence as accurate prediction of maximum seated reach requires balance and pelvis mobility (Reed et al., 2003). The weight of an object being used will also reduce the area in which a person can comfortably perform a task (Sengupta & Das, 1998).

There is no standard approach regarding the evaluation of reach characteristics, as new methods are devised to suit the specific nature of each application. One such study included the use of manikins when designing the interior of a cab for use in heavy vehicles. The manikins were created on the 95^{th} and 5^{th} percentiles of the population and placed in the cockpit. They were used to evaluate and determine maximum and minimum reach characteristics of potential drivers. Digital models were developed based on these manikins and accommodation was then tested (Chaffin & Nelson, 2001).

Evaluation of reach can be done by creating two handed prediction models. Most studies have been limited to a single extremity and that several reach activities involve the use of both arms while simultaneously positioning them towards different target positions or reaching to a target with an arm, while the other was fixed to another location (E. S. Jung & Shin, 2010). It was found that both hands must be considered for reach as it allows for a posture that more accurately mimics real life application.

One method to predict reach characteristics while reaching to targets is discomfort. It was postulated that reach capability would be affected depending on the variances in discomfort between participants. While this is useful for overall reach envelope, it would not produce data regarding the level of comfort, which should be taken into account when designing. While participants may reach to different distances, the location of targets should be placed with regard to the overall level of discomfort. It was found that age group and increased latitude positively correlated with discomfort ratings with elderly participants reporting highest level of discomfort (Wang, Chateauroux, & Chevalot, 2007).

2.6 Modelling

Evaluation of accommodation is required to derive accurate results from the collected data, and there are various methods to do so. Selecting a suitable method is important not only for accuracy but to relate the results to those of similar studies for comparison.

To test the reach capabilities of 26 seated subjects without shoulder restraints in minivans, when introducing different positions for adjustable seats, a reference point from which to measure based on the seat position was necessary. Reach envelopes were taken with respect to the reference point and then translated later for different seat positions (Liu, Ren, Zhang, & Hua, 2017). The seated reach capability was calculated using a reach capability radius which was found to be more easily accomplished and understood than utilizing the Cartesian coordinates of the target points shown below in Figure 5.

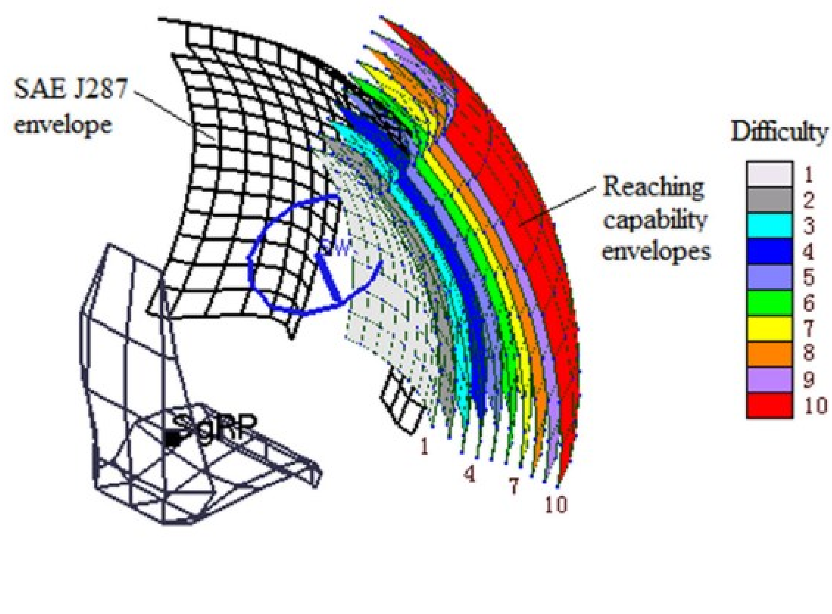

Figure 5 Minimum envelopes of the RCR for the adjustable driver-seat (Liu et al., 2017).

Not content with collected measures, Stoudt was interested in creating equations that would predict functional arm reach from various anthropometric measures. He took several measurements of 100 subjects, constrained by a shoulder harness with 4 inches of slack, as they were asked to reach as though they were going to push a button with their thumb. He subsequently reduced the measurements to 24 reach points he deemed most important and calculated stepwise regressions and he found that elbow to fingertip length and shoulder to fingertip length were the most significant factors in prediction of reach (Stoudt, 1973).

Prediction equations were also used by Konz and Goel to measure the normal working area in the horizontal plane. These equations were derived from the curves of Barnes, Farley, and Squires and were focussed on defining the normal working area. Actual reach measurement data was not acquired, instead, they used forearm and upper arm lengths and projected the resulting curves that assumed these were moving through space. While these models were helpful they did not account for the differences in range of motion between individuals (Konz & Goel, 1969).

There are countless examples of linear regression being used to predict a host of ergonomic applications such as the development of seating accommodation for soldiers in vehicles. Predictive models based on state-of-the-art techniques developed for passenger cars and light trucks, were created using previously acquired data to help define accommodation of seating positions based on posture and the required protective equipment that is worn by military personnel. Using regression equations, it was found that the body armour affected workspace accommodation, and this was taken into account to improve the fit for the soldiers. As such, these were the first seating accommodation models that take into account personal protective equipment and body armour (Zerehsaz, Jin, Ebert, & Reed, 2017).

When testing eye level of pilots, Şenol (2016) generated regression models in order to predict sufficient vision to the exterior of the aircraft. Using the models, it was found with a high degree of accuracy, that any potential visual obstructions could be overcome with further seat adjustments (Şenol, 2016). Linear regression equations allowed the researchers to determine appropriate seating adjustments to accommodate 90% of pilots.

Stewart, Ledingham, Furnace, Schranz, & Nevill (2016) conducted a study concerning egress through a restricted window, comparing success rates with a linear regression analysis. Taking anthropometric measurements and using backwards elimination, they were able to predict the outcome of egress with 75.2% accuracy. Owing to the fact that 25% of participants were misclassified with both Type I and II errors, they identified a major limitation as differences in flexibility since their study treated the body as a rigid object (Stewart et al., 2016).

By using backwards elimination when creating multiple linear regression equations, all predictive anthropometric measurements can be analyzed, allowing only the most predictive to be taken into account (Shao, 1996). This method not only simplifies the equations by reducing the dependent variables to those that are the most predictive, but the predictive ability of the equation is reduced so slightly that it makes no significant difference.

As linear regression is often used and has been shown to be helpful when evaluating cockpit accommodation, the next step is validation. It has been shown that once a predictive equation is created, re-creating it on a smaller subset of the population and testing it against the remaining population is a more accurate method in which to predict the accuracy of the model (Shao, 1993).

Linear regression equations have been shown to be very useful in the analysis of anthropometric and reach envelope data. Using these techniques to build a sound predictive model, one can tell with a high degree of certainty, which measurements are predictive of proper accommodation in a cockpit or any environment which is limited by size.

2.7 Digital Modelling

It is often necessary to understand how a product workplace or task will affect potential users. To address issues in the early stages of design, problems are typically simplified and one or a few body dimensions are considered. The anthropometric measurement is collected from anthropometric data in a reference text (K. Jung, Kwon, & You, 2009). A major drawback to reach data presentation is that it consists of many planar views, and physical models can be time consuming and expensive (Faulkner & Day, 1970). 3D modeling, however, is often more practical to display the appropriate measurements and more effectively analyze them.

In order to reduce the need for physical tests there are benefits from using digital human modeling simulation systems, which can quickly and cheaply facilitate simulations (Chaffin & Nelson, 2001). A digital human modeling tool is a computer program using human models to create, modify and analyze human-machine interactions (Jimmerson, 2001; Nelson, 2001; Thompson, 2001).

Das, Kozey, and Tyson (1994) developed a tool to measure the dynamic maximum reach envelope which would record the data digitally and transfer it to a personal computer for processing and analysis. The computerized potentiometric system for anthropometric measurements (CPSAM) quickly and effectively measures reach envelope with a simple design. Consisting of four potentiometric recording units (PRU), mounted to the wall, each consisiting of a spring loaded pulley and a ten turn, precision type potentiometer with a range of 0 – 10 K ohms. Kevlar string is attached to each of the four pulleys, while the free ends of each string are attached to a common origin on a plexiglass pointer.

Subjects sat in a chair facing the CPSAM and as they held the pointer in their right hand and traced out their maximum reach envelope, the pointer moved through space. As this took place, the length of each kevlar string wase adjusted and the changes corresponded to changes in poteniometer voltage (Biman Das, Kozey, & Tyson, 1994). Digital signals depicting the number of rotations of each potentiometer were then sent to a computer, tracking the movement of the pointer.

Das and Sengupta (1998) used CPSAM to model the entire point cloud as a sphere, rather than a cylinder. Non linear optimization was used to fit the sphere to the data in an attempt to minimize the sum of the error differences, which was found to be within 3cm in both standing and seated positions (Sengupta & Das, 1998).

CPSAM was again used to map the maximum reach envelope of male and female adults in a standing and a seated position. To ensure participants were working within their true maximum, a proprioceptive aid in the form of a back and head rest, to limit trunk motion, was added to the apparatus. Ensuring that the participants remained rested against the aid during the trial was found to limit a source of potential error in the results (Sengupta & Das, 2000).

Other digital modeling techniques have been used as well. When testing optimal seat comfort for pilots, digital manikins were used to evaluate comfort for the 5^{th}, 50^{th} and 95^{th} percentiles of the Indian pilot population with the Delmia Human Software. Testing was done for compression and shear forces on the L4 and L5 vertebrae of the pilots. Various anthropometric measurements were taken. The researchers were able to identify critical design issues involving pilot comfort and seat adjustability for long flights (Gupta, Kalra, Chawla, & Singh, 2018).

3D models of the whole body of Indian pilots based on three sizes, smallest, mean, and largest of the pilot population, were generated from an anthropometric database. They were placed in a 3D prototype of a cockpit using computer software to test visual angles inside and outside. Tools such as view cones, eye view windows, blind spot area, obscuration zone, reflection zone and more were utilized in order to evaluate the visual fields. They were also used to evaluate kinematic body positions of a pilot's body joints during simulated activities (Karmakar, Pal, Majumdar, & Majumdar, 2012). Findings show that the vision analysis tool of digital modelling was not only very effective in terms of position evaluation, but it was instrumental in guiding the design of the cockpit long before the physical prototype was developed.

When Boeing was contracted to design Node I, a connecting passageway between the living and work areas, of the International Space Station (ISS), they were tasked with ensuring that the design was capable of accommodating from the 5^{th} percentile Japanese woman to the 95^{th} percentile American man. In order to facilitate this, proprietary software, Boeing Human Modelling System (BHMS), was used rather than traditional anthropometric testing. This afforded them the ability to prototype designs and analyze them sooner in the design process, as well as save both time and money constructing expensive physical structures. It was found that the cost savings were in excess of $1,000,000, component accessibility was realized, as well as the verification of anthropometric accommodation was validated. Boeing was able to review various procedures and validate the functionality of various maintenance tasks prior to constructing any hardware (Nelson, 2001).

There are two paths to take with digital human modeling tools, either a method based on percentiles of a database of the population, or a custom built method. Percentile methods are often used to produce a 5^{th}, 50^{th} and 95^{th} percentile description according to various anthropometric measurements of a chosen population, which are simulated for design and evaluation. However, the percentile approach may or may not reflect all aspects of the population in size and generalizability can be limited as all users may not be represented (Jimmerson, 2001; K. Jung et al., 2009). Custom built methods use defined values of any anthropometric data desired, often derived in house, which are calculated by regression equations, allowing greater accuracy for accommodation (Jimmerson, 2001; Nelson, 2001; Thompson, 2001). This method however, can be time consuming due to the customizability of the various software applications which was shown using RAMSIS and Jack (K. Jung et al., 2009).

Validity of the generated human models depend on parameters such as the number of human models, design allowance and the relationship between anthropometric variables. However, the programs automatically determine the sizes of body segments once the target population is specified. As well, the digital human modeling systems tested do not allow for input of custom anthropometric databases and only use that of the US Army (K. Jung et al., 2009).

In order to aid in the design of the interior cab in heavy vehicles, manikins based on the 95th and 5th percentiles of the population were derived. Concerned with the upper and lower limits of reach, they were used in place of a host of potential drivers. Digital models were developed based on these manikins and accommodation was tested (Bowman, 2001). It was shown that the use of digital modelling decreased cycle time between concept development and functional validation. However, it was also found that the digital manikins move unrealistically, and that this factor had to be taken into account when optimising the designs.

When proposing design changes for the Australian CT-4A airliner, manikins and percentile tables of Australian anthropometric data were used to confirm space problems within the cockpits. However, when evaluating potential solutions, the manikins proved ill suited to the task and the results were found to be inconclusive. An anthropometric model was devised based on actual pilot measurements, seating positions and measurements of fields of view which was found to provide acceptable results (Anderson & Hendy, 1984).

While motion capture is often used, researchers must be aware that the markers must be visible to the camera at all times. Any movement, even skin movement, can introduce errors into data collection. Also, due to the depth of certain landmarks or areas, it may not be possible to directly map those to the surface of the skin which can also introduce errors into measurements. In this case, estimates of positions need to be made from various other markers. If a single camera is being used, something may pass between the camera and the marker, interrupting data collection. This can often be resolved by using multiple cameras (Roebuck, 1995).

Although digital human modelling systems are widely used to save time and money, they are not necessarily the most accurate. Often, when working with modelling systems, there is a certain level of estimating that is required for a final result. One critical area involves the hands and wrists which are difficult to properly position, which can negatively affect the analysis. Another shortcoming is that the hands of manikins are scaled proportionally to stature, which can lead to unrealistically large hands for taller individuals (Bertilsson, Hogberg, & Hanson, 2010).

While technological advancements have helped ergonomics tremendously, and digital manikins have been shown to reduce cost of development and save time, they are not without their issues. When predicting reach, and more importantly, the difference between various reach types, accurate measures must be paramount.

When reviewing the literature, it becomes clear that with the variance in measurement taking, and the unreliability of various anthropometric databases as well as vast differences in anthropometrics between populations it is important to take new measures of a population ensuring that all procedures are carried out to the standard required. The digital modelling software is also not currently sufficient to accurately conduct reaching tasks with fine detail to distinguish between the various reach and grip types.

Unfortunately, throughout the literature, there is very little quantitative information from which to assess the quality of past models. This makes it difficult to determine how this method compares with previous studies. This holds true for 3-D manikin models as well as regression models.

Chapter 3: Methodology

3.1 Overview

Fifty participants were recruited and evaluated on their ability to complete flight related reaching tasks in a wooden mock aircraft cockpit. Information on the purpose, methods, risks, and benefits of the study were provided to each participant. Anthropometric and demographic measures of the individual were collected as well as the participant's task performance, which is evaluated based on their ability to perform reaching tasks, viewing angles, and clearance measures. Each participant was assigned an alpha numeric code, encoded by a master key that is held by the primary investigator and co-investigators. None of the information about the participants that could be used to identify them was retained. All data were collected in compliance with the Health Science Research Ethics Board at Dalhousie University.

3.2 Participants

Recruitment used print and electronic media announcements posted on campus. A convenience sample of fifty participants, comprised of 30 male and 20 female volunteers, aged 18 – 60, from Dalhousie were recruited. The ratio of the males to females was requested by the DRDC and the age range allowed for a representative sample comparing the general population to pilots. The only exclusion criteria were that participants must have had no reported impediment to range of motion due to injury or other physical limitation in the right upper extremity. All study information was provided along with the voluntary, informed consent form prior to the study. Participants were asked to wear light clothing such as a t-shirt and gym shorts in order to more easily facilitate measuring bodily landmarks and to allow freedom of movement when conducting the experiment. This pilot study was not meant to simulate the effects of movement when wearing the appropriate pilot clothing and personal protective equipment during flight, as it is a proof of concept. Upon arrival at the laboratory, the informed consent form was reviewed with the participant by either the Primary or Co-investigator to ensure that the procedures were completely understood.

3.3 Apparatuses

The study involved two basic measurement procedures and equipment setups. Structural anthropometric dimensions were recorded using standard anthropometric equipment including GPM anthropometer (model 101), GPM anthropometer baseplate (model 101F) and spring scale. Functional reach performance was recorded using a Certus Optotrak (NDI).

Visual and clearance measurements were also performed during the data collection phase. However, they were not included in the creation of the regression models. This study was focused on predicting reach tasks, with visual and clearance data collected to be used in a future study.

Cockpit mock-up

The cockpit mock-up was a wooden test frame used to perform the reaching tasks. The wooden structure was not intended to replicate any particular cockpit design or layout; however, it provided a general setup from which measurements were taken as well as to test reach characteristics and vision tolerances. Reach tests were conducted with the use of sample instrument panels, simulated flight controls, and rudder pedals, used to simulate critical flight tasks. There were 12 reach targets in total, the reach target locations were placed in the cockpit, not to simulate actual flight controls, but to test a variety of reach distances. There was one reach point behind and below the seat. There were 8 reach points up and to the right of the participant, in a line starting slightly behind the seating area to the front of the cockpit. As well, there were 2 additional reach points forward of the seating area at the front of the cockpit and one up and behind the participant's head, on the ceiling of the cockpit.

A solid wall with an opening was placed in front of the participant to simulate a window which was used to detect the vision measurements. The seat in the cockpit was adjustable fore and aft, as well as up and down. All reach measurements were taken from each of the eight seat positions.

Figure 6 Cockpit mock-up.

3.4 Measurements

Structural measurements were obtained in a private location with only the participant and an observer present. The measurement team was comprised of both genders as to allow the ability for a team member of the same sex to gather the measurements upon request.

Anatomical Landmarks

Anatomical landmarks were located both visually and through palpation. Any necessary marks were made using a washable, hypoallergenic eyebrow pencil. Three landmarks needed to be marked, while the others six landmarks were visually identified, as shown below in Figure 6.

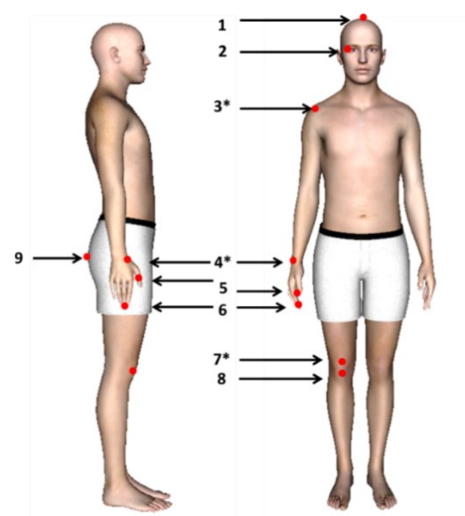

Figure 7. Visual guide to landmark locations. Landmark numbers refer to descriptions provided in **Table 2.** Landmarks indicated with an asterisk (*) were marked with a hypoallergenic eyebrow pencil.

Anthropometric measures

A standardized approach was taken with regard to the structural anthropometric measures. All testers were trained on the use of the measurement equipment to increase inter-rater reliability as much as possible. Relevant measurements were be recorded prior to the commencement of the procedure; they can be viewed below in Table 2.

Table 2. List of Anthropometric measurements and landmarks.

Measurements	Landmark	Landmark #	Instrument
Acromial height, sitting	Acromion (shoulder), right	3	Anthropometer
Buttock-knee length	Knee point,	8	Anthropometer
	Right buttock point	9	Anthropometer
Eye height, sitting	Ectocanthus, right	2	Anthropometer
Knee height, sitting	Suprapatella, right	7	Anthropometer
Stature	Top of head	1	Anthropometer
Biacromial breadth	Acromion (shoulder), right	3	Beam caliper
Sitting height	Top of head	1	Beam caliper
Hand length	Radial stylion	4	Sliding caliper
Arm span	Tip of third phalanges, right and left hands	6	Wall chart
Thumb tip reach	Tip of thumb, right	5	Wall chart
Thumb tip reach (radial stylion)	Radial stylion, right	4	Wall chart
Weight	N/A	N/A	Scale

Reach Measures

Reaching measures were recorded using the NDI Certus Optotrak, a motion tracking system which is capable of fast motion data collection, with a sampling rate greater than 1000Hz, and .01mm resolution with a claimed RMSE is 0.1mm. The Optotrak tracks the 3-D location of Ireds (active markers) in a triad with an attached arm band. A triad was placed on the right arm and forearm of the participant. For the purposes of this study the sampling rate was set to 100 Hz and data were recorded for 2 seconds as the participant held the upper limb in a stationary position pointing to each reach target.

Prior to the collection of the reach trials, a series of test trials were collected to create 5 virtual points on the participant which were the on the participant’s hand at the lateral epicondyle of the humerus, the first index knuckle, thumb tip and middle fingertip, as well as the radial stylion. To obtain these points the participants held the upper stationary and approximately a horizontal position. The Certus stylus was used to touch each of the 4 anatomical landmarks on the hand to record the positions of the virtual points with respect to the triad on the forearm segment. The virtual point of the lateral epicondyle was recorded with respect to the triad on the arm segment.

The first point, the lateral epicondyle was used to establish the forearm-hand reach vector or distance from elbow to the reach target. The second, third and fourth points were to indicate the over/under reach distances for the various types of reach while the virtual point on the stylion was to establish the base measurement for the end of the forearm.

As shown below in Figure 8, all points are mapped to either the triad located on the arm or the forearm. This removes any issue with wrist flexion while reaching affecting reach distances. Since the virtual points on the hand are defined in relation to the triad on the forearm, the wrist and hand can move but it will not affect the location of those points. Although in reality, movement of the hand would shorten the reach measurements, it would only do so slightly. This was intended to be a proof of concept, and as such, followed the directives given by the DRDC.

Figure 8 IREDs in triads attached to both arm and forearm of participant.

No triad was added to the hand due to the fact that this study followed a simplified version of the previously mentioned methodology that Zehner et al. (2002) used. Also, keeping a triad in place on the hand would be more difficult, which would affect the reliability of the measurements.

While this study was completed for aircraft cockpit accommodation, the results are also relevant to any type of seated workstation or vehicle design. All measuring instruments were sterilized with alcohol swabs before and after use on each participant.

3.5 Testing Conditions

Before any testing took place, a series of exercises were performed with the intention of reducing the risk of injury due to repetitive limb movement or posture related issues from the seated position. The detailed warm up routine was taken from the instructions provided by DRDC and included:

Warm Up

- *Bent Over Rotations*: Begin with feet at a comfortable stance wider than shoulder width. Bend over at hips with arms fully extended at sides at 90 degrees from torso. Begin by swinging right arm towards left foot and repeating on opposite side. Continue this motion through comfortable range, but do not strain. Continue this motion for 30 seconds.
- *Arm Circles:* Stand with feet shoulder width apart and knees slightly bent. Raise arms to a 90 degree angle from the torso with arms fully extended. Begin by making small circles by bringing arms forward and gradually increase to a full range of

shoulder motion. Change direction at 15 seconds. Repeat motion with arms moving in opposite direction for 15 seconds.

- *High Knee Hold:* Walking while raising knees to chest: once knee has reached highest point of ROM, pull knee till a slight stretch is felt, continue with movement. Continue motion for 30 seconds alternating legs during walking.

- *Lunge walk and trunk rotation:* Begin by taking a large step in a forward direction and lowering body until the forward knee is at 90 degrees. While at lowest position rotate upper body towards forward leg through full ROM until slight stretch is felt. Bring other leg forward and repeat on other side. Continue lunge walk for 30 seconds.

- *Leg swings (forward/backward):* Participant stands with side to wall, arm length away with hand placed on wall for support. Raising leg closest to wall off of ground and begin by swinging through full ROM. Participant is instructed to swing through full ROM without straining self. 15 seconds on one leg and repeat on opposite leg for 15 seconds.

3.6 In Cockpit Evaluation

The in-cockpit evaluation was based on the participant's ability to adequately reach various targets representing aspects of a control panel, flight controls and adjustable rudder pedals. Sightlines were also detailed to assess the ability of the participant to maintain visual clearances in the aircraft. The purpose of the test was to discover what seat positions are required for participants to accomplish all of the tasks.

Seat Positions

The seat in the cockpit provided approximately 35cm of adjustability in increments of 17.5 cm in the fore/aft and up/down positions. The total range of adjustability was divided twice fore and aft as well as up and down to create a grid of seating positions. The middle position was omitted due to the fact that all reach attempts would be covered by adjacent seat positions. All reaching tasks, visual checks and clearance measures will be taken in each of the 8 possible seating conditions. The 8 seat positions are shown beginning in the lower left below in Figure 7. The seat was adjustable twice forward and twice upward. This order of progression for seat position was maintained for all participants.

6	7	8
4		5
1	2	3

Figure 9. The 8 seat positions in the mock up of the aircraft cockpit.

Seat Posture

The posture adopted by the participant while seated in the cockpit during clearance measures and visual checks was seated, upright with a lap belt fastened around the hips and a shoulder belt keeping the back flat against the seat. Two seated postures were used during the reaching trials. The unrestrained posture was maintained by a lap belt only and the restrained posture included the lap and shoulder belt. This provided data on reach capability of the participants while fully strapped in (constrained) as well as times when they could lean for controls simulating two conditions of flight.

Rudder/Pedal Reach

When flying, a pilot must be able to completely depress the pedals from the seated position. In order to receive a passing score on the rudder/pedal reach test, the participants had to be able to completely depress the pedals with their full foot, a toes only depression resulted in a failure of that test.

Control Reach

Due to the differing nature of the various controls and instrument panels within a cockpit, three types of reach were measured. A pinch grip for turning a dial, depressing or hook grip with index finger for multi-function display buttons or toggle switches, and a power grip for instruments such as the flight stick. Participants reached with their right arm and reach distance was measured from the radial stylion as well as 3 virtual points placed on the participant's hand at the first index knuckle, thumb tip and middle fingertip to indicate the over/under reach distances for the various types of reach. The reach evaluation was marked as a pass/fail score.

Vision

The Design Eye Reference Point is defined as the eye position within a cockpit that provides optimal viewing of all internal and external visual references. For this study it was defined as the imaginary line from the lower sill of the window to a point between the eyes of the participant that subtends an angle of three degrees below the horizontal. Using the dominant eye, participants were asked to look through a sight scope attached to a digital inclinometer to record the angle. Any score not below the three degrees was scored as a failure.

Another test of vision was performed to determine how far below the hood on the instrument panel a participant could see. Vision below the control hood was measured in mm using a ruler with numbers placed in descending order. The lower the number that was visible to the participant, the more of the control panel beneath the control hood was visible.

3.7 Reasonability Test

Upon review, it was apparent that some data obtained during collection was incomplete or incorrect. This could be seen by fields of missing data or measurements that were obviously not possible. If the data could not be accurately corrected, those participants were called back for a second round of testing to correct the erroneous measurements. Although 3 participants were recalled, some reach measurements remained not useable. A reasonability test was performed to determine the validity of the participant's data and remove the incorrect data. To ensure reasonability, the modified results for the 3 participants, with errors omitted, were graphed along with the mean of all data. This graph was compared to other graphs with randomly selected participants reach data along the mean of all data. Both graphs were very similar. This was deemed a reasonable test to ensure the data was valid.

3.8 Data Analysis

Anthropometric measurements were modeled against task and seat performance and the relation between them was modeled in Minitab. Statistical models were derived and validated to determine those with the highest degree of accuracy combined with the highest success rate.

The statistical method used to analyze the data was a method of partial least squares (PLS). It is a common method used in anthropometrics and is well suited when there are more variables than observations and when there is multicollinearity among the variables. PLS is used to reduce predictors to a smaller set of uncorrelated components and performs least squares regression on the components rather than the original data. Components are selected by how much variance is explained in the predictors and between the predictors and the response. If predictors are highly correlated or if less components perfectly model the response, the number of components in the model will be less than the total number of predictors.

Validation

To test the first hypothesis stating maximum reach distances can be accurately modeled from structural anthropometric dimensions, derived linear regression models were recreated using a subset of the sample population, 40 of the 50 participants. The model was tested on the randomly selected, remaining 10 participants to verify its accuracy on a population not used for its creation, as has been shown to be a more accurate method of model selection (Shao, 1993). Once accuracy was deemed acceptable, the model was then able to be used on anyone. The model was based on the same proportion of males and females as the test group, due to the bimodal distribution noted by Pheasant (1996), comparing anthropometrics between men and women. The test was performed 50 times to determine the most appropriate model.

The outcome variables of the model were the R^2 value and the sum of RMS errors. The most acceptable model was one whose R^2 value was most predictive of reach and whose sum of RMS errors when tested on a validation population, most closely matched that of the original model.

The method of validation used to test the second hypothesis stating maximum reach performance can be accurately estimated from reach models, was determined using a contingency table. By testing the measured results versus the predicted results derived from the regression equation, we can see how closely the predicted results match the results that were observed. If they followed the measured results closely, the predicted results were valid. Using the contingency table, the proportion of agreement was calculated by adding the correct reaches and correct misses and dividing by the total reach attempts.

Chapter 4: Results

4.1 Participant Demographics

Structural anthropometric measurements of the 50 participants were recorded and the summarized results displayed for men, women and combined are presented in Tables 3, 4 and 5, respectively. Each table presents the mean, median, and standard deviation as well as the 5^{th}, 50^{th} and 95^{th} percentiles for each dimension. Prior to the calculations, each dataset was tested for normality using the Kolmogorov-Smirnov test and all variables had a p-value of 0.123 or larger, indicating that the measurements were from a normally distributed sample.

Table 3. Anthropometric measures for Males (n=30). All measurements in mm unless otherwise indicated.

	Mean	Median	SD	5th	50th	95th
Sitting Height	1310	1312	34	1256	1312	1369
Acromial Height (Sitting)	997	994	27	965	994	1045
Eye Height (Sitting)	1212	1215	31	1161	1215	1255
Buttock – Knee Length	603	599	27	572	599	645
Knee Height (Sitting)	569	566	31	526	566	621
Bi-acromial Breadth	376	388	39	312	388	427
Hand Length	201	201	11	184	201	220
Stature	1803	1785	65	1719	1785	1912
Arm Span	1813	1811	78	1707	1811	1942
Thumb Tip Reach	824	816	44	761	816	898
Radial Stylion Reach	704	692	43	640	692	772
Weight (kg)	88	89	16	71	89	114

Table 4. Anthropometric measures for Females (n=20). All measurements in mm unless otherwise indicated.

	Mean	Median	SD	5th	50th	95th
Sitting Height	1260	1265	26	1213	1265	1289
Acromial Height (Sitting)	971	968	21	937	968	1007
Eye Height (Sitting)	1163	1165	31	1092	1165	1199
Buttock – Knee Length	588	585	28	535	585	627
Knee Height (Sitting)	527	527	30	474	527	555
Bi-acromial Breadth	339	338	30	285	338	392
Hand Length	185	185	8	169	185	196
Stature	1678	1687	39	1582	1687	1715
Arm Span	1656	1656	57	1543	1656	1727
Thumb Tip Reach	756	739	39	701	739	811
Radial Stylion Reach	643	630	39	594	630	704
Weight (kg)	74	66	19	54	66	117

Table 5. Anthropometric measures for both Males and Females. All measurements in mm unless otherwise indicated.

	Mean	Median	SD	5th	50th	95th
Sitting Height	1290	1285	39	1224	1285	1363
Acromial Height (Sitting)	987	982	28	945	982	1040
Eye Height (Sitting)	1192	1194	39	1130	1194	1243
Buttock – Knee Length	597	594	28	563	594	645
Knee Height (Sitting)	552	546	37	504	546	618
Bi-acromial Breadth	362	361	40	298	361	422
Hand Length	194	194	13	175	194	217
Stature	1753	1744	83	1633	1744	1894
Arm Span	1750	1737	104	1603	1737	1920
Thumb Tip Reach	797	796	54	717	796	883
Radial Stylion Reach	679	682	51	604	682	758
Weight (kg)	83	80	18	61	80	118

4.2 Cockpit Evaluation Measures

The cockpit evaluation measures included the 3-D measurement of reach, visual and clearance measurements. The visual and clearance data presented below is for informational purposes only. It was only collected, not used in the creation of the regression models. The visual measurements assessed the angle of inclination of the participants sight line when looking at certain markers representing viewpoints within and outside of the cockpit. The clearance measurements involved measuring the angle of movement of a flight stick between the legs of the participant as well as fore and aft. Also, measurements were taken of a flight control positioned next to the flight seat. This control was reached by every participant in every seat position.

Angular measurements for vision through the windscreen were gathered along with the linear measurement of vision below the control hood. The results are displayed below in tables 6, 7 and 8 for males, females and all participants respectively.

Table 6. Visual measures for each seat position for males (n=30). Measurements in deg for vision through windscreen, while measurements for vision under control hood in mm.

	Mean	**Median**	**SD**	**5th**	**50th**	**95th**
Vision through windscreen						
Position 1	-13.4	-13.8	1.6	-15.5	-13.8	-10.8
Position 2	-14.4	-14.8	1.8	-16.7	-14.8	-11.8
Position 3	-15.2	-15.5	1.8	-17.4	-15.5	-12.6
Position 4	-15.0	-15.5	1.6	-16.8	-15.5	-12.1
Position 5	-17.3	-17.6	2.1	-20.4	-17.6	-14.2
Position 6	-17.2	-17.6	1.4	-19.2	-17.6	-14.6
Position 7	-18.3	-18.7	1.9	-20.6	-18.7	-15.1
Position 8	-20.0	-20.5	2.1	-22.8	-20.5	-16.6
Vison under control hood						
Position 1	32	32	3	27	32	36
Position 2	35	35	4	29	35	41
Position 3	38	39	4	33	39	45
Position 4	36	36	4	29	36	42
Position 5	42	42	4	35	42	47
Position 6	39	39	3	33	39	43
Position 7	42	42	4	36	42	48
Position 8	47	46	4	41	46	54

Table 7. Visual measures for each seat position for females (n=20). Measurements in deg for vision through windscreen, while measurements for vision under control hood in mm.

	Mean	Median	SD	5th	50th	95th
Vision through windscreen						
Position 1	-11.2	-11.5	1.4	-12.8	-11.5	-9.0
Position 2	-12.3	-12.4	1.6	-14.1	-12.4	-9.8
Position 3	-13.5	-14.0	1.8	-15.5	-14.0	-10.5
Position 4	-13.6	-13.7	1.6	-15.9	-13.7	-11.0
Position 5	-15.7	-16.3	1.6	-18.4	-16.3	-13.1
Position 6	-15.3	-15.6	1.5	-17.2	-15.6	-13.0
Position 7	-16.5	-17.0	1.5	-18.1	-17.0	-13.8
Position 8	-18.6	-18.7	2.4	-21.1	-18.7	-14.9
Vison under control hood						
Position 1	29	29	2	25	29	32
Position 2	31	31	2	27	31	35
Position 3	33	33	8	27	33	37
Position 4	32	32	2	27	32	35
Position 5	37	38	3	34	38	41
Position 6	35	36	2	32	36	38
Position 7	38	39	2	35	39	41
Position 8	43	43	3	37	43	45

Table 8. Visual measures for each seat position for both males and females (n=50). Measurements in deg for vision through windscreen, while measurements for vision under control hood in mm.

	Mean	Median	SD	5th	50th	95th
Vision through windscreen						
Position 1	-12.5	-12.3	1.8	-15.2	-12.3	-9.5
Position 2	-13.6	-13.6	2.0	-16.5	-13.6	-10.0
Position 3	-14.6	-14.5	2.0	-17.3	-14.5	-10.7
Position 4	-14.5	-14.5	1.8	-16.6	-14.5	-11.4
Position 5	-16.7	-16.6	2.0	-20.0	-16.6	-13.6
Position 6	-16.5	-16.7	1.7	-18.6	-16.7	-13.3
Position 7	-17.6	-17.6	1.9	-20.3	-17.6	-14.3
Position 8	-19.5	-19.3	2.3	-22.8	-19.3	-16.1
Vison under control hood						
Position 1	31	30	3	26	30	36
Position 2	33	33	4	27	33	39
Position 3	36	36	6	31	36	44
Position 4	34	34	4	29	34	40
Position 5	40	40	4	34	40	46
Position 6	37	37	3	33	37	43
Position 7	41	40	4	35	40	47
Position 8	45	45	4	39	45	53

During the in-cockpit measurements, participants were tested to determine their ability to completely depress the foot pedals in each seat position. A successful pedal depression was recorded simply as a 1, while unsuccessful attempts were recorded with a 0. As well, there is often a hand control next to the right-hand side of the seat, that remains in place as the seat is adjusted. A participant's ability to completely manipulate the control was tested in each seat position and recorded with a 1 for full control manipulation or a 0 for inability to completely manipulate the control. In table 9, the results for pedal depression and side control manipulation are recorded for males, females, and all participants.

Table 9. Measures for ability to depress pedal for each seat position for males (n=30), females (n=20) and both males and females (n=50), shown as total successful participants, 1 = depressed and 0 = not depressed. Results for ability to use side control shown as total successful participants, measured as 1 = successful and 0 = unsuccessful.

	Males	**Females**	**All Participants**
Depress Pedal			
Position 1	18	1	19
Position 2	30	14	44
Position 3	30	19	49
Position 4	13	0	13
Position 5	30	18	48
Position 6	7	0	7
Position 7	22	3	25
Position 8	28	11	39
Use Side Control			
Position 1	50	50	50
Position 2	50	50	50
Position 3	50	50	50
Position 4	50	50	50
Position 5	50	50	50
Position 6	50	50	50
Position 7	50	50	50
Position 8	50	50	50

During the in-cockpit measurements, participants were asked to move a flight stick attached to the floor of the cockpit, as far forward (fore) as possible and back (aft) toward the participant as possible. At each maximum fore and aft position, the angular orientation with respect to the vertical was recorded. This was to determine how seat position affected the range of motion of the flight stick. In tables 10, 11, and 12 the measurements in degrees for the angles of the flight stick for men, women and both men and women respectively.

Table 10. Angles of flight stick (fore and aft) for each seat position for males (n=30) measured in degrees.

	Mean	**Median**	**SD**	**5th**	**50th**	**95th**
Angle Fore						
Position 1	0.2	0.5	4.1	-5.1	0.5	9.0
Position 2	5.9	4.4	4.3	0.7	4.4	13.2
Position 3	11.4	10.5	6.2	6.1	10.5	21.5
Position 4	0.7	0.4	4.2	-4.5	0.4	9.8
Position 5	11.8	11.0	4.5	6.7	11.0	19.4
Position 6	0.4	0.0	4.3	-4.6	0.0	9.8
Position 7	5.4	4.8	4.0	0.3	4.8	12.3
Position 8	10.7	11.1	4.1	4.9	11.1	16.4
Angle Aft						
Position 1	-34.6	-34.0	4.2	-36.2	-34.0	-31.9
Position 2	-27.8	-28.5	2.1	-28.7	-28.5	-24.0
Position 3	-14.8	-14.8	0.1	-14.9	-14.8	-14.7
Position 4	-33.1	-33.2	1.6	-35.3	-33.2	-30.7
Position 5	-13.6	-13.6	0.2	-13.9	-13.6	-13.3
Position 6	-32.0	-31.9	1.6	-34.3	-31.9	-29.7
Position 7	-25.3	-25.9	2.0	-26.2	-25.9	-22.0
Position 8	-14.6	-14.6	0.3	-14.9	-14.6	-14.0

Table 11. Angles of flight stick (fore and aft) for each seat position for females (n=20) measured in degrees.

	Mean	Median	SD	5th	50th	95th
Angle Fore						
Position 1	-4.1	-4.5	2.9	-7.8	-4.5	-0.9
Position 2	0.7	0.4	3.4	-2.6	0.4	5.9
Position 3	5.0	5.0	2.7	1.8	5.0	8.3
Position 4	-2.5	-4.3	4.8	-7.1	-4.3	5.0
Position 5	5.3	4.9	2.8	2.3	4.9	8.9
Position 6	-4.6	-4.3	3.0	-8.4	-4.3	-0.4
Position 7	0.0	0.2	2.4	-2.7	0.2	2.7
Position 8	4.8	4.7	2.7	1.2	4.7	8.3
Angle Aft						
Position 1	-36.2	-35.8	4.5	-39.1	-35.8	-31.6
Position 2	-28.2	-28.5	0.9	-28.8	-28.5	-26.1
Position 3	-14.7	-14.7	0.1	-14.8	-14.7	-14.6
Position 4	-35.3	-34.5	5.1	-38.3	-34.5	-30.9
Position 5	-13.6	-13.6	0.2	-13.9	-13.6	-13.2
Position 6	-33.1	-33.5	1.8	-35.0	-33.5	-29.7
Position 7	-25.8	-26.0	1.0	-26.4	-26.0	-23.9
Position 8	-14.7	-14.7	0.3	-15.0	-14.7	-14.4

Table 12. Angles of flight stick (fore and aft) for each seat position for both males and females (n=50) measured in degrees.

	Mean	Median	SD	5th	50th	95th
Angle Fore						
Position 1	-0.8	-0.9	4.3	-7.0	-0.9	7.1
Position 2	4.6	4.0	4.6	-2.1	4.0	12.6
Position 3	9.9	10.1	6.2	1.9	10.1	20.3
Position 4	-0.1	-0.8	4.5	-6.2	-0.8	7.7
Position 5	10.3	9.5	5.0	2.9	9.5	19.2
Position 6	-0.8	-1.9	4.6	-6.3	-1.9	8.5
Position 7	4.1	2.8	4.3	-2.6	2.8	11.1
Position 8	9.2	8.9	4.6	3.1	8.9	16.1
Angle Aft						
Position 1	-35.2	-34.6	4.3	-37.4	-34.6	-31.7
Position 2	-27.9	-28.5	1.8	-28.7	-28.5	-24.9
Position 3	-14.7	-14.8	0.1	-14.9	-14.8	-14.6
Position 4	-33.9	-33.8	3.5	-36.2	-33.8	-30.6
Position 5	-13.6	-13.6	0.2	-13.9	-13.6	-13.2
Position 6	-32.4	-32.9	1.7	-34.8	-32.9	-29.5
Position 7	-25.5	-25.9	1.7	-26.2	-25.9	-23.4
Position 8	-14.6	-14.7	0.3	-15.0	-14.7	-14.1

During the in-cockpit measurements, participants were asked to allow a flight stick attached to the floor of the cockpit to move as far left (port) as possible and right (starboard) possible while the angles were measured. This procedure was to determine how seat position affected the range of motion of the flight stick from side to side. The angles were recorded when the flight stick met the participant's leg. If the flight stick did not come into contact with the participants legs, a measurement was not taken, and the participant's score was omitted. In tables 13, 14, and 15 the measurements in degrees for the angles of the flight stick for men, women and both men and women, respectively.

Table 13. Angles of flight stick (port and starboard) for each seat position for males (n=30) measured in degrees.

	Mean	**Median**	**SD**	**5th**	**50th**	**95th**
Angle Port						
Position 1	-	-	-	-	-	-
Position 2	15.5	15.0	1.9	13.6	15.0	17.8
Position 3	15.0	14.5	2.8	11.5	14.5	19.6
Position 4	-	-	-	-	-	-
Position 5	14.8	14.6	2.8	11.0	14.6	19.4
Position 6	-	-	-	-	-	-
Position 7	15.7	15.7	-	15.7	15.7	15.7
Position 8	14.7	14.6	2.6	10.8	14.6	18.7
Angle Starboard						
Position 1	-	-	-	-	-	-
Position 2	13.8	13.6	2.9	10.2	13.6	16.9
Position 3	14.5	14.5	2.7	10.3	14.5	19.1
Position 4	-	-	-	-	-	-
Position 5	13.4	13.4	2.3	10.0	13.4	17.3
Position 6	-	-	-	-	-	-
Position 7	13.2	13.2	-	13.2	13.2	13.2
Position 8	12.8	12.8	2.7	8.8	12.8	17.4

Table 14. Angles of flight stick (port and starboard) for each seat position for females (n=20) measured in degrees.

	Mean	Median	SD	5th	50th	95th
Angle Port						
Position 1	-	-	-	-	-	-
Position 2	-	-	-	-	-	-
Position 3	11.1	10.3	3.0	8.7	10.3	15.8
Position 4	-	-	-	-	-	-
Position 5	11.9	12.4	3.5	6.4	12.4	16.6
Position 6	-	-	-	-	-	-
Position 7	-	-	-	-	-	-
Position 8	11.5	11.6	2.9	6.9	11.6	16.0
Angle Starboard						
Position 1	-	-	-	-	-	-
Position 2	-	-	-	-	-	-
Position 3	11.0	11.4	2.7	7.0	11.4	14.6
Position 4	-	-	-	-	-	-
Position 5	10.9	10.6	2.9	7.1	10.6	14.9
Position 6	-	-	-	-	-	-
Position 7	-	-	-	-	-	-
Position 8	10.0	9.2	3.0	5.8	9.2	15.0

Table 15. Angles of flight stick (port and starboard) for each seat position for both males and females (n=50) measured in degrees.

	Mean	Median	SD	5th	50th	95th
Angle Port						
Position 1	-	-	-	-	-	-
Position 2	15.5	15.0	1.9	13.6	15.0	17.8
Position 3	13.5	13.1	3.4	9.3	13.1	19.1
Position 4	-	-	-	-	-	-
Position 5	13.7	14.0	3.4	8.3	14.0	19.0
Position 6	-	-	-	-	-	-
Position 7	15.7	15.7	-	15.7	15.7	15.7
Position 8	13.5	13.6	3.1	8.4	13.6	18.4
Angle Starboard						
Position 1	-	-	-	-	-	-
Position 2	13.8	13.6	2.9	10.2	13.6	16.9
Position 3	13.1	13.2	3.2	8.6	13.2	18.7
Position 4	-	-	-	-	-	-
Position 5	12.4	12.4	2.8	7.9	12.4	17.1
Position 6	-	-	-	-	-	-
Position 7	13.2	13.2	-	13.2	13.2	13.2
Position 8	11.8	12.0	3.1	7.3	12.0	16.8

Reach Results

The observed reach results are arranged in order of seat position and reach target. The success rate of the reaches is displayed as a percentage of overall reach attempts. In Tables 16 and 17, shown below, results are organized by reach attempts with and without the shoulder harness, respectively.

Table 16. Percentage of observed participants who reached target successfully organized by chair position (Rows) and reach target (columns)

	Percentage of participants who successfully reached target (Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	96	98	98	72	16	2	0	0	0	0	100
2	100	94	98	98	98	46	2	0	0	0	0	94
3	98	44	98	98	98	82	30	2	0	0	0	80
4	98	98	100	98	94	32	4	0	0	0	0	100
5	80	76	98	100	100	96	36	2	0	0	0	82
6	94	100	100	100	98	40	2	0	0	0	0	100
7	96	96	100	100	100	78	22	0	0	0	0	100
8	64	90	100	100	100	98	48	2	0	0	0	92

Table 17. Percentage of observed participants who reached target successfully organized by chair position (Rows) and reach target (columns)

	Percentage of participants who successfully reached target (No Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	98	98	100	100	82	30	6	0	34	48	100
2	100	96	100	100	100	98	68	24	0	82	86	98
3	94	68	98	100	100	98	92	40	8	96	96	82
4	100	100	100	100	100	92	56	14	0	46	66	98
5	100	90	100	100	100	100	98	66	16	100	100	94
6	100	100	100	100	100	100	82	24	0	44	66	100
7	100	100	100	100	100	100	98	54	10	96	98	100
8	98	94	100	100	100	100	100	90	34	100	100	94

4.3 Data Analysis

Multiple linear regression, multiple linear regression with backwards elimination and partial least squared (PLS) were tested and compared to find the most favourable method of statistical regression. To make this comparison, four points were chosen in which there was a split between those who reached and who did not. The four points were seat position 1 – point 5, seat position 2 – point 6, seat position7 – point 6 and seat position 8 – point 7. Regression equations were made for each reach point using the methods described. The calculated reach results were compared with the observed results, and the differences noted for all 3 types of regression. The mean difference between each method and the observed results were collected as shown below in table 18.

Table 18. Comparison of calculated reach outcomes from Regression, Backwards Elimination and Partial Least Squares against observed reach outcomes.

Method	Regression	Backwards Elimination	PLS
Position 1 – Point 5 Harness			
Type I Errors	2	3	4
Type II Errors	5	0	0
Total Number of Errors	7	3	4
Position 2 – Point 6 Harness			
Type I Errors	10	9	8
Type II Errors	1	1	1
Total Number of Errors	11	10	9
Position 7 – Point 6 Harness			
Type I Errors	3	11	5
Type II Errors	7	1	3
Total Number of Errors	10	12	8
Position 8 – Point 7 Harness			
Type I Errors	5	21	7
Type II Errors	4	0	0
Total Number of Errors	9	21	7
Total Number of Errors between methods	37	46	28

As seen in the table above, the method with the least number of errors compared with the observed result is PLS with 28 errors across 200 reaches. Second is full regression with 37 and backward elimination was last with 46 errors. While backwards elimination is meant to only remove statistically nonsignificant beta coefficients, removing these variables clearly decreases the quality of the prediction.

Shao (1993) has shown with regression equations that a validated model (models that undergo construction-validation procedures) produces a more useful equation, therefore the added robustness of the PLS method with the built-in validation, along with the least number of errors, makes it the most suited method to calculate the equations. In the end, with the same predictor variables between all 3 methods, after validation, all methods should arrive at the same equation.

PLS Data

When the MATLAB code was written to determine whether a participant did or did not reach a particular target, the distance calculated was the Euclidian distance between the two points. If the participant's reach was beyond the reach target, a positive value was assigned to the number, if it was short, a negative value was assigned. As one cannot reach directly through an object, a buffer of 10mm was introduced into the calculation to account for any error related to reaching past and to the side of the reach target. Tables 19 and 20 present the results of the data analysis of each point during each chair position with both harness condition and non harness condition respectively using PLS for data analysis.

Table 19. Percentage of calculated participants who reached target successfully organized by chair position (Rows) and reach target (columns)

	Percentage of participants who successfully reached target (Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	92	98	98	52	8	0	0	0	0	0	94
2	100	90	98	100	92	22	0	0	0	0	0	100
3	98	46	100	100	98	76	12	0	0	0	0	64
4	98	100	100	100	80	16	0	0	0	0	0	98
5	76	90	100	100	100	88	14	0	0	0	0	86
6	100	100	100	100	96	20	0	0	0	0	0	98
7	98	100	100	100	100	54	10	0	0	0	0	100
8	32	96	100	100	100	98	36	0	0	0	0	98

Table 20. Percentage of calculated participants who reached target successfully organized by chair position (Rows) and reach target (columns)

	Percentage of participants who successfully reached target (No Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	100	100	100	98	72	16	0	0	16	14	100
2	100	100	100	100	100	98	50	10	0	42	74	100
3	100	60	98	100	100	100	86	20	0	98	100	96
4	100	100	100	100	100	98	30	10	0	20	30	100
5	100	98	100	100	100	100	100	32	10	100	98	100
6	100	100	100	100	100	100	72	16	0	20	30	100
7	100	100	100	100	100	100	98	20	0	96	100	100
8	100	100	100	100	100	100	100	76	16	100	100	100

In Tables 21 and 22, the percentage of agreement is displayed between the observed reach results and the calculated reach results derived from the MATLAB code. They are separated by the harness and non harness condition.

Table 21. Percentage of Agreement between observed and calculated reach results organized by chair position (Rows) and reach target (Columns).

	Percentage of participants who successfully reached target (No Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	92	100	100	80	88	98	100	100	100	100	94
2	100	92	100	98	94	76	98	100	100	100	100	94
3	100	74	98	98	100	94	82	98	100	100	100	64
4	96	98	100	98	86	84	96	100	100	100	100	98
5	76	78	98	100	100	92	78	98	100	100	100	80
6	94	100	100	100	98	80	98	100	100	100	100	98
7	94	96	100	100	100	72	80	100	100	100	100	100
8	64	90	100	100	100	100	84	98	100	100	100	94

Table 22. Percentage of Agreement between observed and calculated reach results organized by chair position (Rows) and reach target (Columns).

	Percentage of participants who successfully reached target (No Harness)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	100	98	98	100	98	90	86	94	100	82	66	100
2	100	96	100	100	100	100	78	82	100	56	80	98
3	94	72	100	100	100	98	86	76	92	94	96	86
4	100	100	100	100	100	94	74	88	100	74	64	98
5	100	92	100	100	100	100	98	66	86	100	98	94
6	100	100	100	100	100	100	86	92	100	76	60	100
7	100	100	100	100	100	100	100	66	90	96	98	100
8	98	94	100	100	100	100	100	86	82	100	100	94

Differences in reach types

When analyzing the 3 types of reach, the regression analysis not only for middle fingertip reach but also once for both the hook grip and the power grip would need to be performed. However, when determining the methodology in measuring the different types of reach, virtual points on the hand were selected as the measurement for those reaches. This means that when looking at the data, those points within each participant should be a constant distance away from the virtual point assigned to the middle fingertip. Therefore, it was not necessary to rerun the regression equation but rather a simple adjustment could be made to each distance to determine if the point was reachable or not.

To demonstrate this point, 10 participants were chosen at random, along with 10 reach points to see if the data reflected the assumption about virtual point consistency. Participants 10, 18, 41, 16, 25, 29, 35, 28, 47, and 14 were chosen, along with reach points 84, 144, 82, 80, 41, 138, 24, 178, 90, and 179. When looking at the differences, we can see the consistency between the measurements below for all participants in Table 23.

Table 23. Table showing average difference between the reach points and M F Tip for all 10 participants.

			Average Reach Distances					Difference Between M F Tip &		
Reach Trial	Seat Pos.	Reach Point	Harness Y=1/N=0	M F Tip	T Tip	Knuckle	Stylus	T Tip	Knuckle	Stylus
24	1	12	0	61	-2	-35	-126	64	96	188
41	2	5	0	76	11	-22	-115	65	98	191
80	4	8	1	-378	-442	-475	-569	64	96	190
82	4	10	1	-522	-586	-619	-713	64	96	190
84	4	12	1	95	31	-2	-96	64	96	190
90	4	6	0	66	2	-31	-124	64	96	190
138	6	6	0	85	21	-12	-106	64	96	190
144	6	12	0	100	36	4	-90	64	96	190
178	8	10	1	-304	-368	-400	-495	64	96	191
179	8	11	1	-290	-354	-386	-481	64	96	191

The results are not without error; however, they are consistent across the sample. Because the difference between reach distances remained constant throughout the reach trials and across participants, it has been deemed sufficient to use the distance measurements calculated from the MATLAB code and substitute them in the existing regression equations rather than calculating new equations for each type of reach.

Doing so, the reach distance measurements for each of the randomly selected participants were changed with the reach distances for the other types of reach. Below in

Tables 24, 25 and 26, are the reach distances for a representative number of reach targets for all 3 types of reach.

Table 24. Reach distance calculations in mm of various reach points for select participants.

Fingertip Reach Distance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	99	31	13	-570	88	14	44	142	-94	-357
Participant	14	100	60	50	-530	116	37	53	137	-46	-317
Participant	16	90	29	12	-588	94	-3	22	125	-97	-373
Participant	18	56	54	42	-587	20	34	92	121	-55	-364
Participant	25	47	130	138	-484	25	116	139	107	71	-256
Participant	28	98	115	119	-460	118	111	127	146	47	-240
Participant	29	90	105	107	-480	88	90	108	131	29	-261
Participant	35	81	93	92	-529	116	70	95	128	11	-300
Participant	41	69	81	77	-542	81	52	79	120	-9	-319
Participant	48	101	70	63	-526	128	48	68	142	-29	-309

Table 25. Reach distance calculations in mm of various reach points for select participants.

Hook Grip Reach Distance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	49	-19	-37	-620	38	-36	-6	92	-144	-407
Participant	14	32	-8	-18	-598	48	-31	-15	69	-114	-385
Participant	16	39	-22	-39	-639	43	-54	-29	74	-148	-424
Participant	18	9	7	-5	-634	-27	-13	45	74	-102	-411
Participant	25	-11	72	80	-542	-33	58	81	49	13	-314
Participant	28	13	30	34	-545	33	26	42	61	-38	-325
Participant	29	10	25	27	-560	8	10	28	51	-51	-341
Participant	35	2	14	13	-608	37	-9	16	49	-68	-379
Participant	41	7	19	15	-604	19	-10	17	58	-71	-381
Participant	48	43	12	5	-584	70	-10	10	84	-87	-367

Table 26. Reach distance calculations in mm of various reach points for select participants.

Power Grip Reach Distance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	10	-58	-76	-659	-1	-75	-45	53	-183	-446
Participant	14	0	-40	-50	-630	16	-63	-47	37	-146	-417
Participant	16	8	-53	-70	-670	12	-85	-60	43	-179	-455
Participant	18	-28	-30	-42	-671	-64	-50	8	37	-139	-448
Participant	25	-53	30	38	-584	-75	16	39	7	-29	-356
Participant	28	-9	8	12	-567	11	4	20	39	-60	-347
Participant	29	-25	-10	-8	-595	-27	-25	-7	16	-86	-376
Participant	35	-15	-3	-4	-625	20	-26	-1	32	-85	-396
Participant	41	-27	-15	-19	-638	-15	-44	-17	24	-105	-415
Participant	48	5	-26	-33	-622	32	-48	-28	46	-125	-405

Once reach distances are determined, performance measures can be taken on reach. Below in Tables 27, 28, and 29 are the performance measures taken for the randomly selected participants and the representative reach points described above.

Table 27. Performance calculations of various reach points for select participants.

Fingertip Reach Performance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	1	1	1	0	1	1	1	1	0	0
Participant	14	1	1	1	0	1	1	1	1	0	0
Participant	16	1	1	1	0	1	1	1	1	0	0
Participant	18	1	1	1	0	1	1	1	1	0	0
Participant	25	1	1	1	0	1	1	1	1	1	0
Participant	28	1	1	1	0	1	1	1	1	1	0
Participant	29	1	1	1	0	1	1	1	1	1	0
Participant	35	1	1	1	0	1	1	1	1	1	0
Participant	41	1	1	1	0	1	1	1	1	1	0
Participant	48	1	1	1	0	1	1	1	1	0	0

Table 28. Performance calculations of various reach points for select participants.

Hook Grip Reach Performance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	1	0	0	0	1	0	1	1	0	0
Participant	14	1	1	0	0	1	0	0	1	0	0
Participant	16	1	0	0	0	1	0	0	1	0	0
Participant	18	1	1	1	0	0	0	1	1	0	0
Participant	25	0	1	1	0	0	1	1	1	1	0
Participant	28	1	1	1	0	1	1	1	1	0	0
Participant	29	1	1	1	0	1	1	1	1	0	0
Participant	35	1	1	1	0	1	1	1	1	0	0
Participant	41	1	1	1	0	1	1	1	1	0	0
Participant	48	1	1	1	0	1	1	1	1	0	0

Table 29. Performance calculations of various reach points for select participants.

Power Grip Reach Performance											
Reach Trial		**24**	**41**	**52**	**82**	**84**	**90**	**138**	**144**	**175**	**179**
Seat Position		**1**	**2**	**3**	**4**	**4**	**4**	**6**	**6**	**8**	**8**
Reach Point		**12**	**5**	**4**	**10**	**12**	**6**	**6**	**12**	**7**	**11**
Harness	**(1=Y,0=N)**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**
Participant	10	1	0	0	0	1	0	0	1	0	0
Participant	14	1	0	0	0	1	0	0	1	0	0
Participant	16	1	0	0	0	1	0	0	1	0	0
Participant	18	0	0	0	0	0	0	1	1	0	0
Participant	25	0	1	1	0	0	1	1	1	0	0
Participant	28	1	1	1	0	1	1	1	1	0	0
Participant	29	0	1	1	0	0	0	1	1	0	0
Participant	35	0	1	1	0	1	0	1	1	0	0
Participant	41	0	0	0	0	0	0	0	1	0	0
Participant	48	1	0	0	0	1	0	0	1	0	0

Using a contingency table, the proportion of agreement was calculated by adding the correct reaches and correct misses and dividing by the total reach attempts across all reach types and reach points. Overall, the proportion of agreement = (A+D)/n =

(5995+3029)/9600 = 0.94 which means that the PLS models were correct 94% of the time.

Table 30. Contingency table for all reaches with all participants.

		Predicted		
	Reach	Yes	No	
Observed	Yes	5995	124	6119
	No	452	3029	3481
		6447	3153	9600

Of course, 94% is not perfect as it leaves 6% error. As seen above in table 30, there are 576 incorrect calculated reaches spread between the upper right and lower left quadrants of the contingency table. These two quadrants represent the two types of error, Type I and Type II respectively. Type I error is a reach that is predicted to be a miss but, when compared with observed data, was a successful reach. Type II error is a predicted successful reach when the observed data indicates it was a missed reach.

Chapter 5: Discussion

The selection of aircrew candidates for pilots is complicated by the physical space requirements of the cockpit and the obvious requirement that any pilot must "fit" into the space and effectively perform all the task requirements associated with flying the aircraft. This requires a methodology to appropriately select potential candidates based upon his or her anthropometric characteristics from the pool of candidates. The primary aim of this project was to determine if, through statistically based modelling of 50 participants, reach and reach performance measures could be accurately predicted using structural anthropometric dimensions within a simulated aircraft cockpit. Participants were tested on reaching ability for 12 reach points across 8 seat positions and two harness conditions in the simulated cockpit. The overall goal of the study was to help preselect individuals for the role of pilot based on his or her structural anthropometry without performing accommodation studies on all potential candidates and to identify a subset of the potential candidates for which physical accommodation studies may be necessary to make a final determination on his or her suitability (fit).

5.1: Models

Model Selection

Upon completion of data collection, determining a method of analysis was necessary to effectively analyzing the data. Regression analysis is often used for determining the strength of predictors, for instance, determining the strength of the effect that independent variables have on the dependent variable. Regression analysis can also help to predict future values or trends. For this study, 3 methods of regression analysis were considered, multiple linear regression, Multiple linear regression with backward elimination and PLS.

Multiple linear regression attempts to assess if a continuous dependent variable can be predicted from one or more independent variables, or how much variance in a continuous dependent variable is explained by a set of predictors. Different regression selection approaches are helpful in testing predictors, thereby increasing efficiency of analysis.

The standard method is the simultaneous addition of variables. Each predictor is assessed as if it were entered after all other predictors were already in the equation, then assessed by what it offers to the overall prediction equation and how it differs from the other variables that are entered. This analysis is most appropriate when dealing with a low number of predictors and when researchers do not know which variables will create the best prediction equation.

Multiple linear regression with backward elimination is the reverse of the standard process. All independent variables are added to the prediction equation at once, and then each is removed individually to assess how the model performs in its absence. If the removal of the variable does not significantly change the prediction model, the variable is left out.

PLS is a technique that reduces predictors to a smaller set of uncorrelated components and performs least squares regression on those components rather than the original data. This type of regression is especially useful when predictors are highly collinear or when there are more predictors than observations. Unlike multiple regression, PLS does not assume the predictors are fixed, meaning that predictors can be measured with error making this a more robust to measurement uncertainty. PLS emphasizes making a predictive model and is not commonly used to screen out variables. Components are selected by how much variance is explained in the predictors and between the predictors and the response. If predictors are highly correlated or if less components perfectly model the response, the number of components in the model will be less than the total number of predictors.

Model fitting is important to consider when selecting the model for analysis. An increase in explained variance of the model (typically expressed as R^2) in a linear regression model will always happen when adding independent variables. However, adding too many variables to the model leads to overfitting which is the reduction of the model generalizability. A simple model is often preferable to one which is more complex. Statistically, due to chance alone, a model with a large number of variables will have some that are statistically significant.

As detailed in the results, PLS was chosen based on two factors. The first factor was that when tested along side the other two methods, the total value of errors when compared to the observed reach data was comparable to that of multiple linear regression, which had the least amount of total error. The second factor was that while performing the regression, validation could be performed automatically. With multiple linear regression and multiple linear regression with backwards elimination, the validation process would have had to be done manually. Choosing PLS saved a significant amount of time as the built-in validation made it the most suited method to calculate the equations. It should not be dismissed however that all three methods, using the same predictor variables, should arrive with the same equation after being properly validated.

Performance

Using PLS with validation, 192 statistical models were created that reasonably predicted the reach distance of the participants. While deriving accurate reach measurements for accommodation prediction is important, it is just as important to test those models against actual reach performances to determine their usefulness.

Among all 192 models, the R^2 ranged from a low of 14.6% to a high of 84.2% with a median R^2 of 55%. The standard error of the measurement (SEM) ranged from a low of 23mm to a high of 123mm, averaging at 47mm. When broken down by models with the harness and without, there were some differences. Models with the shoulder harness have an R^2 range of 17.2% for the low to a high of 84.2%, averaging at 60.8%. While the SEM ranges from a low of 23mm to a high of 123mm, averaging at 44mm. Models without the shoulder harness had an R^2 values from a low of 14.6% to a high of 81.0%, averaging at 49.2%. The SEM ranged from a low of 26mm to a high of 121mm, averaging at 50mm. Distributions of the R^2 values for all models, as well as for all harness models and no harness models individually can be seen below in Figures 10, 11, and 12.

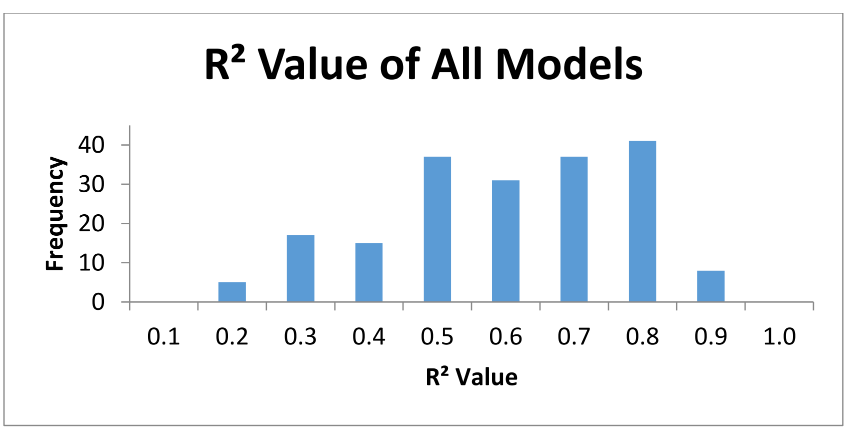

Figure 10. Distribution of R^2 values of all models.

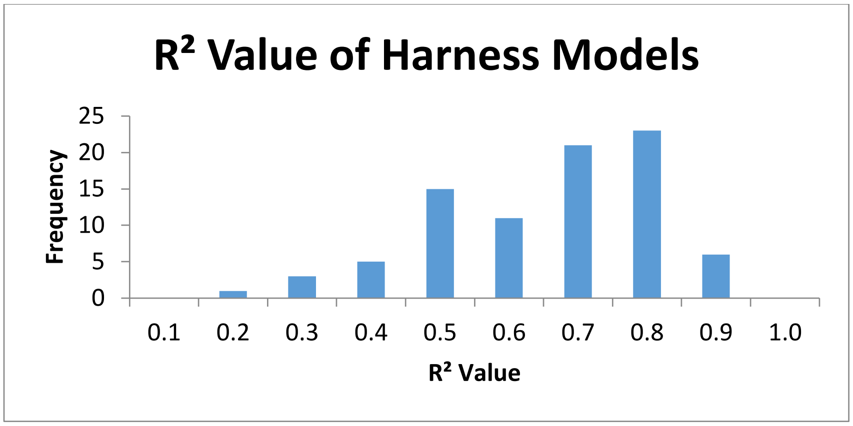

Figure 11. Distribution of R^2 values of harness models.

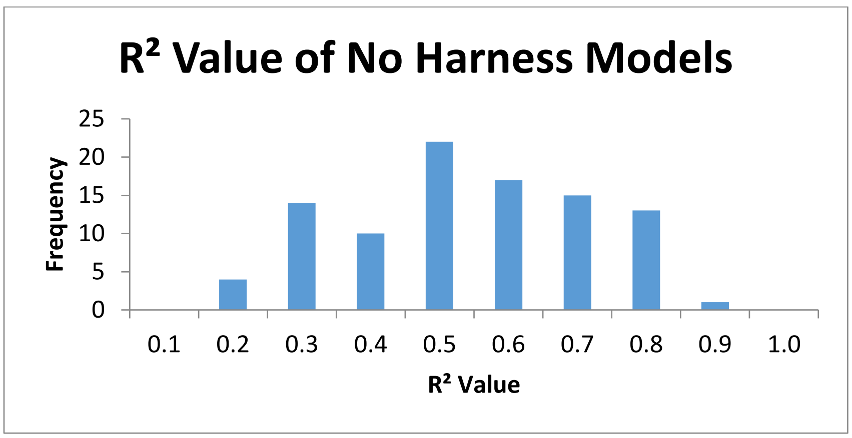

Figure 12. Distribution of R^2 values of no harness models.

Similarly, distributions for the SEM values (in mm) for all models, as well as harness models and no harness models individually can be seen below in Figures 13, 14 and 15.

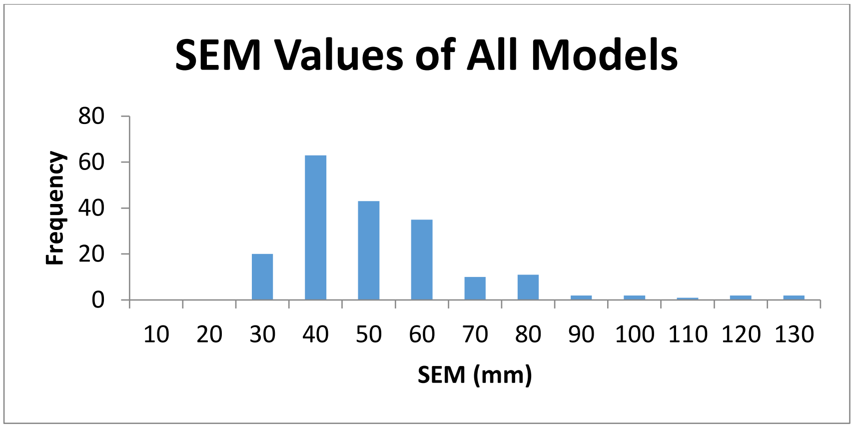

Figure 13. SEM values of all models

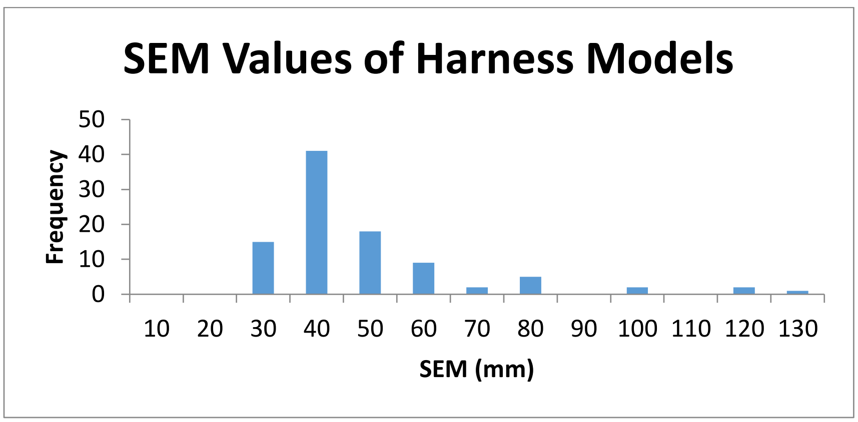

Figure 14. SEM values of harness models

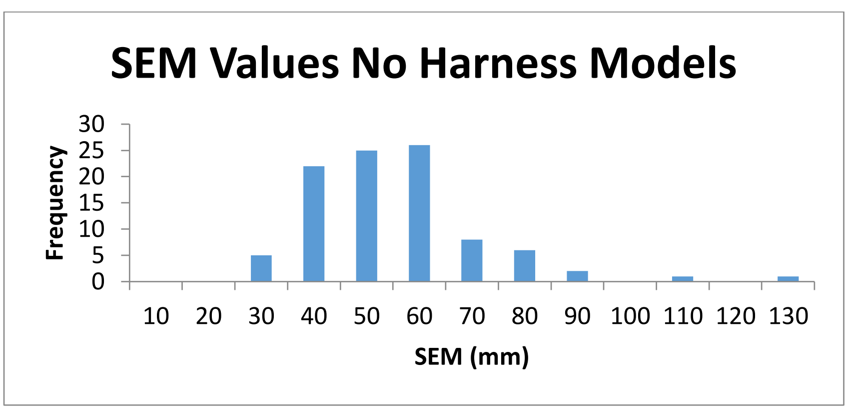

Figure 15. SEM values of no harness models

When split between model conditions for with and without harness, the results are fairly similar. It was expected that the models without the harness would have a lower R^2 rating due to the extra degree of freedom with the addition of torso range of motion however, it does not seem to be the case.

The models were able to accurately predict reach distance within just under 50mm which is not unreasonable. Considering the heterogeneous convenience sample of participants with varying anthropometric measurements as well as the over representation of females, the R^2 values are also reasonable. This demonstrates the value of this proposed methodology for future use. Unfortunately, there are no other models with which to compare as information is scarce. Using the models to test the predicted reach performance of the participants compared to the observed results yielded a success rate of 94%. With the results from the contingency table, it was determined that when predicting reach performance, the models worked.

Regardless of the success of the models, there was still error, and closely analyzing the results can help to determine the source. Statistical modelling can lead to two basic types of error notably Type 1 – successful accomplishment of the task when it is predicted to be a failure and Type 2 – unsuccessful completion of the task when it is predicted to be accomplished. Type 1 errors indicate the model predicted a missed reach when in fact, the participant reached. This type of error would lead to screening out potential pilots based on an inaccurate model. Type 2 errors, where a participant was predicted to have reached a control when, in reality they did not, is more dangerous. This could be crucial in life-or-death situations. Type 2 errors should be reduced. Using a contingency table to validate the results of the study shows that there are more Type 2 errors than Type 1.

Individual characteristics such as sex, anthropometry and seated conditions (position and restraints) were considered to be important factors in determining successful reach performance. To determine where the error originated, the results were divided into groups, males vs. females and harness vs. no harness as seen in Appendix F. The rate of Type 2 errors was the same between the sexes for both harness conditions as well as between harness conditions with both sexes. The results were further broken down between the sexes for each harness condition. Males vs. females for reach trials with a harness as well as males vs. females for reach trials without a harness. In the end, no significant difference was found in the rate of error. The results show that no one characteristic significantly contributed to the error rate.

A comparison of buffer sizes was made to determine whether it accounted for the rate of error. A buffer size of 25mm was selected to compare against the 10mm buffer size from the study in order to determine the effect on the results. When comparing the error rates between the two buffer sizes, there is a difference in both Type 1 and 2 errors. With the 10mm buffer, 1% of reaches were Type 1 errors while 5% of reaches were type 2 errors. Using a buffer of 25mm 2% or reaches were Type 1 errors while 3% of reaches were Type 2.

Overall, the results remained consistent when split by harness conditions, by the sex of the participants or any combination of the two. Without previous studies to compare, it is always difficult to assess, however, 94% is a good result. Others in the future now have something with which to compare their work.

5.2: Buffer sizes

The buffer size of 10mm, which is 100 times the claimed RMSE for the Optotrak, was chosen for two reasons, the first is straight forward as it was the buffer used in the Matlab code when calculating the observed reach conditions. It was employed to allow the code to record a reached point when the measurements did not agree with the results. As the reach points are physical points in space, the participant can not reach directly into or through it. A buffer of 10mm was implemented to allow the computer to record a reach when the participant had reached to the side of the target or when they could touch the target but were stopped short due to the size of the wooden target. The second reason was to ensure to minimize Type 1 errors. The larger the buffer size, the greater the chance of introducing Type 1 error.

5.3: Accuracy

Thinking logically about the process of developing a regression equation and using it to accurately predict a measurement, one might become lost in the pursuit of accuracy while losing focus of what they are trying to achieve. Though a buffer of 10mm was selected, the variability of the models themselves average $\pm$ 50mm from the given prediction. Using a buffer of 10mm, it is impossible to determine whether a participant reached the target. This means that if the reach distance within 50mm of the target, the requirements for a pass or fail in the measurements can not be distinguished from the variability within the model.

That is not to say these models are inaccurate, just that they can be improved upon. With the evolution of technology, digital manikins or avatars, became a viable option to be used in place of live participants in ergonomic fitting trials. The introduction of digital modelling helped to speed up production in various industries as well as reduce the cost of using live participants. When employing digital manikins, researchers will often design avatars to the 5th, 50th and 95th percentiles of the population or develop proprietary methods incorporating a multivariate approach to boundary conditions of key anthropometric dimensions and substitute them for participants, saving both time and money (Chaffin & Nelson, 2001). However, as previously stated, there is nothing written in the literature regarding their accuracy when compared to humans. It does not make sense to wait until technology is perfected, as that may never happen, but one needs to have realistic expectations of the model's performance, both strengths and weaknesses.

This method was unique in the literature, however, it was based closely on the methods employed by Zehner et al. (2002). The main component of this study, not found in the literature, was determining the accuracy of the model. Without a comparison of the model to real world results, there is no way to determine its efficacy. Going forward, this will give others something to compare their models to.

5.4: Costs

The models in this study, while not perfect, show that this method would help reduce costs. Using the existing methods, one could simply send those who fall into either Type 1 or 2 error for fit mapping. This would reduce number of candidates in need of fit-mapping while ensuring those who fall within the error tolerances are not unjustly dismissed as not fitting.

Given the accuracy of the regression equations, out of 1000 participants, only 50-75 might need to be physically tested through the fit-mapping process. By using the models to correctly pass or reject 94% of the participants, the entire process is sped up as only those who fall within the error rates of the models would need further testing to determine whether they can be accommodated in the aircraft. This is a significant cost savings compared with testing every participant.

5.5: Choice

With this method, an issue arises of whether one models for in flight safety to reduce the risk of lives lost because a pilot could not successfully complete a task or to reduce the chance of falsely rejecting a suitable pilot and reduce potential lawsuits. A buffer size should be chosen based on the desired outcome. If attempting to ensure no participant is falsely rejected, a larger buffer size should be used. If the focus is on safety and the reduction of Type 1 errors, a smaller buffer should be used. Unfortunately, you can not prioritize the reduction of both types of errors, a choice must be made because prioritizing one type of error increases the other.

While this aim of this study was to demonstrate a proof of concept that a statistically based model could be developed, and then to analyze the strengths and limitations of the process rather than produce final models for use by the RCAF, it does raise the question of what is needed for more robust models.

Considering the models created in this study, it is clear that as a proof of concept, they do produce accurate results. If this methodology were to be used to select for pilot accommodation, one would need to develop more robust models. This would require a larger sample size, as well as more clearly defined cockpit constraints and a more robust measurement system.

5.6: Limitations and Future Direction

During the study, there were some measurements that were not properly measured in large part due to the constraints of the 3d capture system. While most reach positions worked well, the fact that all active markers needed to be in view of the camera during measurement, made some of the measurements of the complex reaches more difficult to ascertain. Reaches that involved moving the arm up and back over the head were among the most problematic and participants often had to reach in unnatural ways to position the markers for the camera to be able to read them.

The equations are prone to error with such a small sample. With a larger pool of participants from which to draw, a robust set of equations could be developed that would yield more accurate results. This would reduce overall variability and the buffer size could then be reduced with more accurate results.

To implement this concept more accurately, a representative sample of participants would be required. Ideally a sample of pilots, or participants who closely match the anthropometrics of pilots. The participants in this study were a convenience sample and their anthropometrics varied drastically at times. This was intentional, as overall accuracy was not the goal of this study, but going forward, a more homogeneous population would improve accuracy.

Of course, to develop models for use in the RCAF, one would need to devise an accurate test cockpit and place reach points at the proper locations for key controls and other necessary parts of the cockpit for flight.

5.7: Final Thoughts

The purpose of the study was to determine whether regression analysis was a suitable method to predict reach and performance measures of potential pilots in an aircraft cockpit for the RCAF. Using a convenience sample of 50 participants, it was determined that it is a valid method for modelling reach and performance for aircraft cockpits as well as any other work environment. With the models derived from the study, the error rate was 6%, and the fit mapping process could be reduced to those solely who fall into type 1 or 2 errors.

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Appendix A. Consent Form

CONSENT FORM FOR VOLUNTARY HUMAN PARTICIPATION IN RESEARCH PROJECTS

Protocol Number: 2017-016

Research Project Title: Evaluation of a Novel Methodology to Evaluate Workspace Accommodation

Principal Investigator: Allan Keefe, (416) 635-2126

I,________________(name) of ____ (address and phone number) hereby volunteer to be a participant in the study: Evaluation of a Novel Methodology to Evaluate Workspace Accommodation (Protocol #2017-016). I have read the information sheet and have had the opportunity to ask questions of the Investigator(s). All of my questions concerning this study have been fully answered to my satisfaction. However, I may obtain additional information about the research project and have any questions about this study answered by contacting Allan Keefe (416-635-2126).

I understand that my participation in this study will involve one data collection session of approximately two hours duration using an aircraft cockpit mock-up located at Dalhousie University's School of Health and Human Performance.

I understand that my participation in this study will involve:

1. I will be asked to don athletic wear (e.g. shorts, t-shirt) and anthropometric measurements will be taken to quantify my body size. Measurements will be obtained using tradition tools such as calipers and anthropometer. This information will be used to determine the relationship between body size and the ability to perform in-cockpit tasks and meet fit criteria.

    a. Anatomical features will be marked on my body using a hypoallergenic makeup pencil to aid the measures in performing accurate and consistent measurements

    b. A measurement team will be composed of a measurer and a data recorder, which may include members of each gender. On request, measurements on my body will be taken by an measurer of the same gender

2. I will then sit in an aircraft cockpit mock-up and be evaluated on my ability to perform workspace accommodation tasks such as reaching instrument panel controls and rudder pedals, achieving acceptable sightlines and meeting a head clearance criterion.

Photographic imagery may be taken to document the study and aid in data analysis. All imagery will be kept in a secure and confidential database unless I explicitly provide permission to use my image in DND approved scientific publications or presentations. My face will always be digitally blurred to ensure that I am not recognizable and that my participation remains anonymous.

I have been told that the principal risks of the research protocol are minor muscular aches and pains that may arise from repetitive reaches to my range of motion limits. By performing a dynamic warm-up routine before participating, it is anticipated that these effects will be minimized. I understand that some people may experience minor skin irritation may result from skin cleaning with alcohol wipes and landmarking. All instruments will be cleaned with alcohol wipes before use and the potential for skin irritation will be reduced by using hypoallergenic make-up pencils for drawing landmarks. I consider these risks acceptable.

Also, I acknowledge that my participation in this study, or indeed any research, may involve risks that are currently unforeseen by Defence Research and Development Canada (DRDC).

I understand that my experimental data will be protected under the Government Security Policy (GSP) at the appropriate designation and not revealed to anyone other than the DRDC-affiliated Investigator(s) or external investigators from the sponsoring agency without my consent except as data unidentified as to source.

I understand that my name will not be identified or attached in any manner to any publication arising from this study. Moreover, I understand that the experimental data may be reviewed by an internal or external audit committee with the understanding that any summary information resulting from such a review will not identify me personally.

I understand that, as a Government Institution, DRDC is committed to protecting my personal information. However, under the Access to Information Act, copies of research reports and research data (including the database pertaining to this project) held in Federal government files, may be disclosed. I understand that prior to releasing the requested information, the Directorate of Access to Information and Privacy (DAIP) screens the data in accordance with the Privacy Act in order to ensure that individual identities (including indirect identification due to the collection of unique identifiers such as rank, occupation, and deployment information of military personnel) are not disclosed.

I understand that I am free to refuse to participate and may withdraw my consent without prejudice or hard feelings at any time. Should I withdraw my consent, my participation in this research project will cease immediately, unless the Investigator(s) determine that such action would be dangerous or impossible (in which case my participation will cease as soon as it is safe to do so). I also understand that the Investigator(s) or their designate may terminate my participation at any time, regardless of my wishes.

I have been informed that the research findings resulting from my participation in this research project may be used for commercial purposes.

Secondary Use of Data: I understand that my data from this study may be used in unidentified form in future related studies provided review and approval have been given by DRDC Human Research Ethics Committee.

For Everyone:
I understand that by signing this consent form I have not waived any legal rights I may have as a result of any harm to me occasioned by my participation in this research project beyond the risks I have assumed. Also, I understand that I will be given a copy of this consent form so that I may contact any of the individuals mentioned below at some time in the future should that be required.

Release granting permission to use photo or video image capture from an Approved Human Research Study in Department of National Defence Publications and Presentations

Initial One:

______ I hereby **grant** permission to use photo or video capture of me from the above study in DND publications and presentations. My **facial features will be blurred so that I may not be recognized in the image.**

______ I **do not grant** permission to use photo or video capture of me from the above study in DND publications and presentations.

Volunteer's Name:____

Signature:___________________________ Date:___________________________

Principal Investigator

Signature: ________________________________ Date:___________________________

Notes:

Investigator

I have verbally briefed the participant of the requirements for this research experiment.

Signature: __ Date:___________________________

FOR PARTICIPANT ENQUIRY IF REQUIRED:

Should I have any questions or concerns regarding this project before, during or after participation, I understand that I am encouraged to contact the appropriate DRDC research centre cited below. This contact can be made by surface mail at this address or by phone or email to any of the DRDC numbers and addresses of individuals listed below:

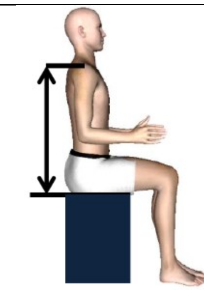
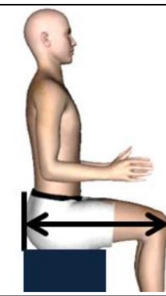
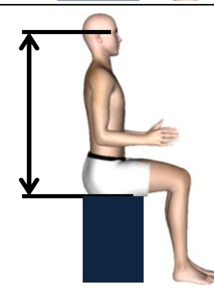
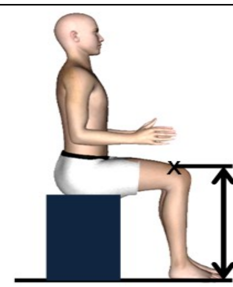
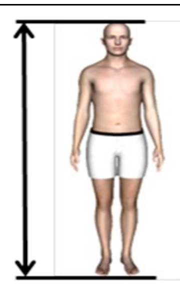
Defence R&D Canada - Toronto

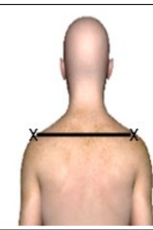
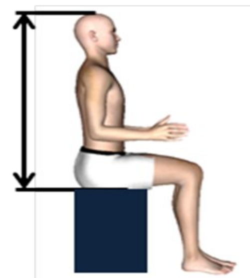
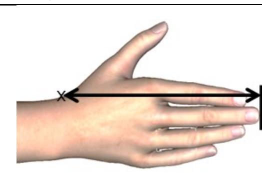
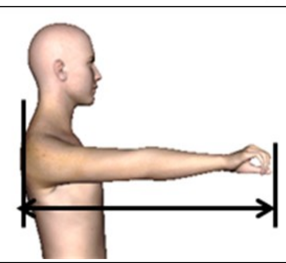
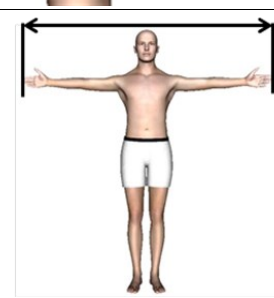
1133 Sheppard Avenue West
Toronto, Ontario, M3K 2C9

Allan Keefe. Email: allan.keefe@drdc-rddc.gc.caor Telephone: (416) -635-2126

For research ethics issues, Chair, DRDC Human Research Ethics Committee (HREC), contact by email: HREC-CEESH-Toronto@drdc-rddc.gc.ca; or by phone: (416) 635-2098

Appendix B. List of Anthropometric Measures

Measure	Description	Visual Guide
Acromial Height, Sitting	Vertical distance between a sitting surface and the acromion landmark on the tip of the right shoulder.	
Buttock-Knee Length	The horizontal distance between a buttock plate placed at the most posterior point of either buttock and the anterior point of the right knee.	
Eye Height, Sitting	The vertical distance between a sitting surface and the ectocanthus landmark on the outer corner of the right eye	
Knee Height, Sitting	The vertical distance between a footrest surface and the suprapatella landmark.	
Stature	The vertical distance from a standing surface to the top of the head.	

Biacromial Breadth	The distance between the right and left acromion landmarks on the tips of the shoulder.	
Sitting Height	The vertical distance between a sitting surface and the top of the head	
Hand Length	The length of the right hand between the stylion landmark on the wrist and the tip of the middle finger (dactylion Ill).	
Thumbtip Reach	The horizontal distance between a back wall and the right thumbtip of the outstretched arm is measured on a wall scale.	
Arm Span	The distance between the tips of the middle fingers of horizontally outstretched arms.	

Appendix C. Recruitment Poster

VOLUNTEERS WANTED FOR RESEARCH STUDYING ADVANCED AIRCREW ACCOMODATION MODELLING

We are looking for volunteers for a research study conducted by the Division of Kinesiology at Dalhousie University looking at two statistical methods for the evaluation of the importance of different body dimensions on your ability to reach to series of reach targets. Participation involves 1 visit, lasting approximately 1.5 hours in duration where participants will have body measurement, range of motion and maximum reach envelope tested.

You may be eligible to participate if you:

✓ Between 18 - 60 years of age

You will not be eligible to participate if you:

×Have a decreased arm range of motion because of injury or other physical limitations

You would be asked to report to the Biodynamics, Ergonomics and Neuroscience Laboratory located in Room 217 of the Dalplex (6260 South Street). For more information about this study, or to volunteer, please contact Colleen Dewis at (benlab@dal.ca) or 902-494-2066.

Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066	Reach accommodation study benlab@dal.ca or Colleen at 902-494-2066

APPENDIX D: Participant Data (Anthropometric Measures)

Table 31. Anthropometric Measures for participants 1 through 25.

Participant	Sex (0=Male, 1=Female)	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length
1	1	1235	964	1122	574
2	0	1293	968	1219	573
3	1	1280	1007	1205	626
4	1	1265	968	1186	592
5	1	1224	942	1151	579
6	1	1220	936	1123	605
7	0	1249	963	1164	587
8	0	1286	976	1199	607
9	0	1305	1028	1227	627
10	1	1224	956	1144	602
11	0	1281	977	1196	585
12	1	1273	971	1162	623
13	1	1299	965	1199	594
14	0	1271	969	1159	580
15	0	1309	1001	1210	578
16	1	1264	957	1161	571
17	1	1246	983	1138	571
18	1	1281	993	1196	651
19	1	1282	1014	1186	528
20	0	1368	1037	1267	644
21	1	1253	973	1170	561
22	0	1325	1034	1240	576
23	1	1272	968	1166	562
24	1	1257	967	1163	591
25	0	1374	1042	1243	632

Table 32. Anthropometric Measures for participants 1 through 25.

Participant	Sex (0=Male, 1=Female)	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature
1	1	476	298	168	1633
2	0	586	321	213	1795
3	1	542	289	182	1715
4	1	473	335	188	1645
5	1	512	284	174	1624
6	1	544	344	188	1683
7	0	563	299	195	1727
8	0	586	312	190	1787
9	0	572	318	204	1807
10	1	523	300	180	1633
11	0	562	312	192	1738
12	1	546	336	174	1712
13	1	541	396	192	1719
14	0	571	362	189	1714
15	0	567	325	190	1764
16	1	526	338	177	1572
17	1	552	392	184	1703
18	1	517	354	181	1677
19	1	616	372	195	1711
20	0	593	431	205	1883
21	1	533	333	184	1677
22	0	526	349	188	1749
23	1	505	346	185	1670
24	1	527	338	195	1712
25	0	620	398	222	1898

Table 33. Anthropometric Measures for participants 1 through 25.

Participant	Sex (0=Male, 1=Female)	Arm Span	Thumb Tip Reach	Thumb Tip Reach (Radial Stylion)	Weight (kg)
1	1	1535	702	596	64
2	0	1798	816	680	88.2
3	1	1632	789	679	91
4	1	1638	783	660	66.3
5	1	1641	743	636	63.6
6	1	1688	786	676	72.7
7	0	1734	809	683	84
8	0	1853	812	686	80
9	0	1827	758	640	121
10	1	1575	731	616	84
11	0	1757	750	621	80.7
12	1	1680	789	683	77.7
13	1	1692	718	606	65.9
14	0	1711	764	641	92.8
15	0	1776	823	700	72.8
16	1	1598	701	593	60.8
17	1	1724	790	684	102.4
18	1	1618	734	615	118.6
19	1	1668	819	704	117
20	0	1924	882	757	101.5
21	1	1637	730	611	60.9
22	0	1704	800	694	90.8
23	1	1608	730	603	54.5
24	1	1700	731	623	61.3
25	0	1868	866	732	92

Table 34. Anthropometric Measures for participants 26 through 50.

Participant	Sex (0=Male, 1=Female)	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length
26	0	1338	976	1243	671
27	0	1264	982	1181	576
28	0	1314	994	1216	613
29	0	1320	993	1225	594
30	0	1241	947	1143	571
31	0	1356	1016	1243	573
32	0	1278	968	1196	599
33	0	1308	981	1190	629
34	0	1325	1005	1232	607
35	0	1328	993	1228	606
36	0	1327	1053	1234	583
37	0	1293	982	1191	601
38	0	1324	1000	1213	613
39	0	1278	985	1165	566
40	0	1323	1000	1242	599
41	0	1309	1009	1205	597
42	1	1211	944	1085	611
43	0	1331	1018	1235	636
44	1	1249	963	1139	610
45	1	1288	988	1181	564
46	1	1287	1004	1190	570
47	1	1283	964	1188	579
48	0	1279	977	1173	575
49	0	1370	1048	1265	645
50	0	1325	1001	1210	639

Table 35. Anthropometric Measures for participants 26 through 50.

Participant	Sex (0=Male, 1=Female)	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature
26	0	578	441	213	1890
27	0	568	371	201	1769
28	0	594	388	218	1851
29	0	621	392	210	1830
30	0	548	387	200	1700
31	0	520	355	183	1764
32	0	562	360	202	1782
33	0	610	385	216	1888
34	0	541	391	196	1805
35	0	533	404	193	1761
36	0	534	423	184	1757
37	0	544	405	203	1773
38	0	564	402	204	1852
39	0	545	365	184	1724
40	0	559	391	196	1837
41	0	536	397	196	1772
42	1	549	369	196	1692
43	0	606	420	208	1850
44	1	528	347	187	1663
45	1	504	342	190	1706
46	1	506	334	181	1690
47	1	516	337	197	1715
48	0	527	362	196	1765
49	0	614	414	211	1924
50	0	631	411	222	1942

Table 36. Anthropometric Measures for participants 26 through 50.

Participant	Sex (0=Male, 1=Female)	Arm Span	Thumb Tip Reach	Thumb Tip Reach (Radial Stylion)	Weight (kg)
26	0	1865	910	784	99.6
27	0	1830	791	673	72.2
28	0	1912	884	749	78.6
29	0	1902	815	690	84.1
30	0	1815	779	658	75.4
31	0	1691	772	657	72.6
32	0	1786	809	684	75
33	0	1914	914	792	91.4
34	0	1720	852	733	104.5
35	0	1806	856	743	96.1
36	0	1763	834	726	144.5
37	0	1832	847	740	90.4
38	0	1850	843	718	91.5
39	0	1710	781	671	68.3
40	0	1770	776	663	72.7
41	0	1739	805	683	89.8
42	1	1790	809	676	63.6
43	0	1857	852	758	97.2
44	1	1673	774	665	78.2
45	1	1665	724	612	53.7
46	1	1647	716	614	66
47	1	1711	811	710	64.8
48	0	1756	808	690	70.2
49	0	1957	841	717	93.2
50	0	1960	877	742	79.5

Appendix E: Reasonability Test

As outlined in the methodology, section a series of reasonability checks were performed on the 3-D data files prior to any analysis. The checks included any reach point greater than plus or minus one metre as well as other criteria. When data was identified as either missing or incorrect, the original data files were visually checked and then processing was rerun for these participants. If, upon double checking the data, the problems still occurred, it was decided whether the data points should be removed, or if there were enough points that were incorrect, the participants were requested to come back and retake the testing for certain points. Three participants were retested, and while this corrected several measurements, some errors were still present in the new data usually due to the loss of line-of-sight between the sensors and the cameras.

Rather than remove all the participants data, it was decided to remove the incorrect data. Figure 1 shows the reaches for participants 8, 13, 17 and 22 plotted against the mean. To determine which data was incorrect, all reaches for the problem participants were graphed against the mean reaches for all subjects. This made it easier to determine outlier points that were not in agreement with the majority of reaches.

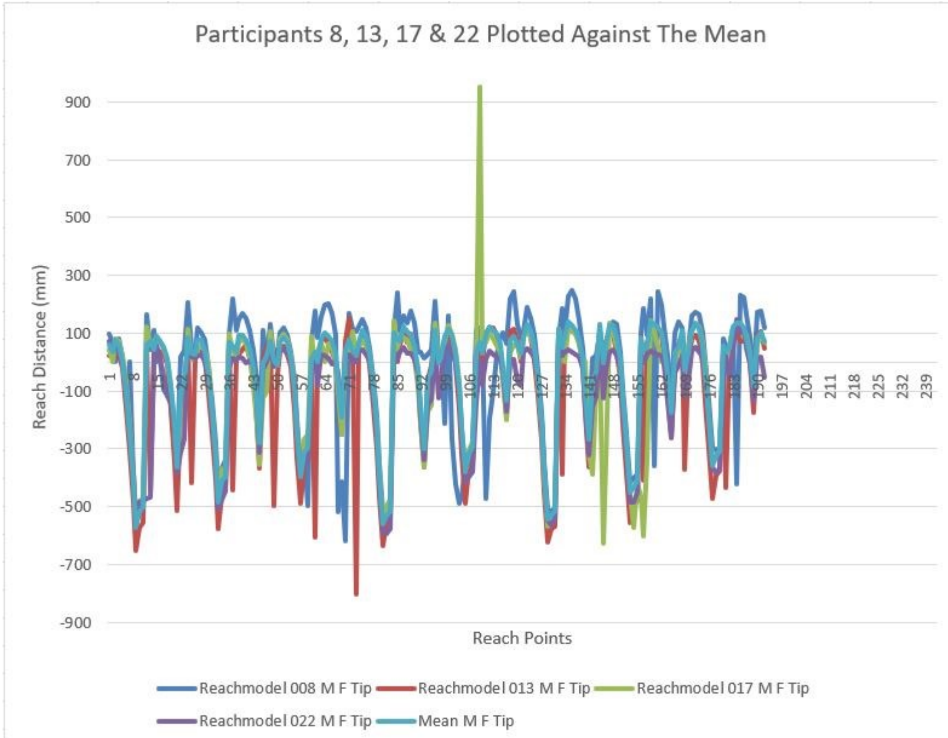


Figure 16. Reach distances for participants 8, 13, 17 and 22 plotted against the reach distances for the mean before correction.

This visual representation of the points was used as a reference of where errors may be. These erroneous points were selected and overwritten in the master file as NaN which stands for not a number, allowing the MATLAB code to go through the data and not assign a value for the particular reach point as it would with a value of 0. Once the erroneous data was removed, the data for the four participants followed the mean much more closely as shown below in Figure 2.

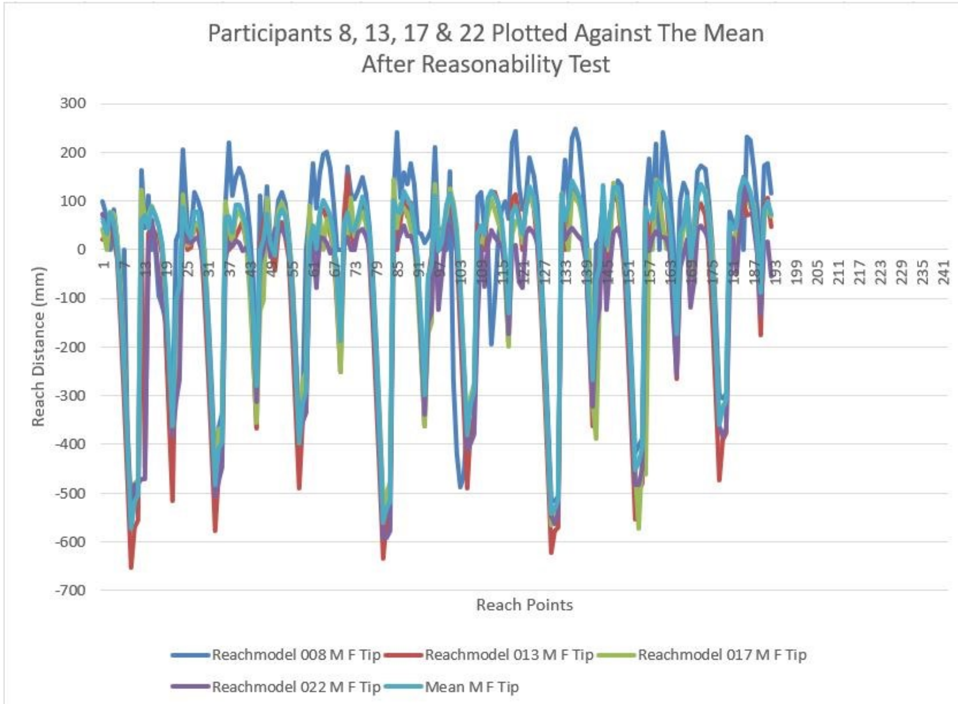


Figure 17. Reach distances for participants 8, 13, 17 and 22 plotted against the reach distances for the mean after the reasonability test.

To determine whether this was a process which should be conducted on all participants, a random sample of participants were chosen several times and graphed against the mean. Figure 3 below, shows one such sample. The data from the participants matches the reach data of the mean of all participants very closely.

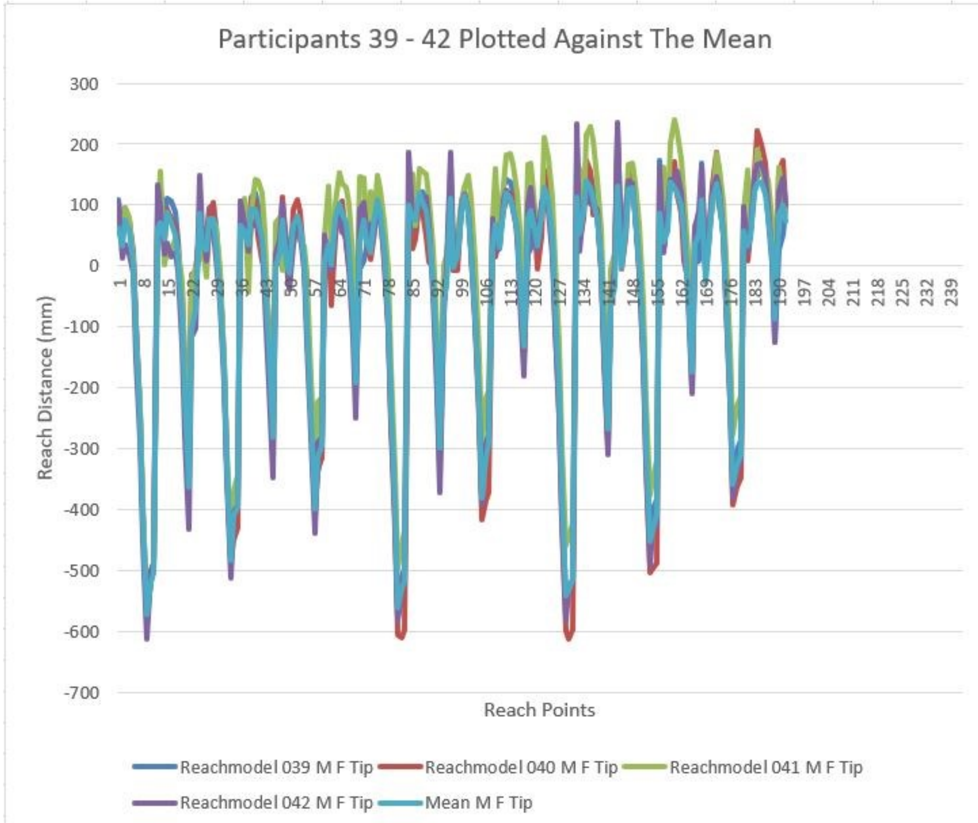


Figure 18. Reach distances for participants 39 – 42 plotted against the reach distances for the mean.

After graphing several individual results against the mean for comparison, it was determined that the method of flagging and removing obvious outliers in the master file was a suitable reasonability test.

APPENDIX F: Contingency Tables

Table 37. Contingency table for all reaches with all participants.

	Reach	Predicted Yes	Predicted No	
Measured	Yes	5995	124	6119
	No	452	3029	3481
		6447	3153	9600

Table 38. Contingency table for all reaches by males.

	Reach	Predicted Yes	Predicted No	
Measured	Yes	3830	74	3904
	No	271	1585	1856
		4101	1659	5760

Table 39. Contingency table for all reaches by females.

	Reach	Predicted Yes	Predicted No	
Measured	Yes	2165	50	2215
	No	181	1444	1625
		2346	1494	3840

Table 40. Contingency table for harness reaches with all participants.

		Predicted		
	Reach	Yes	No	
Measured	Yes	2396	64	2460
	No	182	2158	2340
		2578	2222	4800

Table 41. Contingency table for no harness reaches with all participants.

		Predicted		
	Reach	Yes	No	
Measured	Yes	3599	60	3659
	No	270	871	1141
		3869	931	4800

Table 42. Contingency table for harness reaches by male participants.

		Predicted		
	Reach	Yes	No	
Measured	Yes	1548	37	1585
	No	102	1193	1295
		1650	1230	2880

Table 43. Contingency table for harness reaches with female participants.

		Predicted		
	Reach	Yes	No	
Measured	Yes	848	27	875
	No	80	965	1045
		928	992	1920

Table 44. Contingency table for no harness reaches with male participants.

	Predicted			
	Reach	Yes	No	
Measured	Yes	2282	37	2319
	No	169	392	561
		2451	429	2880

Table 45. Contingency table for no harness reaches with female participants.

	Predicted			
	Reach	Yes	No	
Measured	Yes	1317	23	1340
	No	101	479	580
		1418	502	1920

Table 46. Contingency for all reaches with all participants with a 25mm buffer.

	Predicted			
	Reach	Yes	No	
Measured	Yes	6136	227	6363
	No	311	2926	3237
		6447	3153	9600

APPENDIX G: PLS Models with Validation

Table 47. PLS Models w/ Validation for chair position 1, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
1	Y	1	26.5835	-0.1392	-0.168	-0.149	0.0554	0.2079	0.0777	0.4122	0.0331	0.0804	0.0615	0.0791	48.7%	33.72
1	Y	2	-782.329	0.095	0.111	0.093	0.084	0.113	0.08	0.329	0.055	0.046	0.061	0.061	62.8%	31.8
1	Y	3	-1064.48	0.13	0.15	0.1	0.11	0.16	0.12	0.45	0.08	0.06	0.09	0.09	77.4%	33.78
1	Y	4	-1087.67	0.14	0.2	0.13	0.12	0.15	0.12	0.44	0.08	0.06	0.09	0.1	81.6%	27.68
1	Y	5	-1157.59	0.1	0.16	0.12	0.13	0.16	0.12	0.45	0.08	0.06	0.1	0.1	73.7%	33.59
1	Y	6	-1241.4	-0.03	0.2	-0.04	0.06	0.51	0.15	0.96	0.11	0.12	0.05	0.0	74.9%	36.33
1	Y	7	-1350.11	-0.01	0.14	-0.09	0.07	0.5	0.14	0.83	0.1	0.12	0.1	0.11	77.3%	36.13
1	Y	8	-1708.62	0.14	0.17	0.11	0.15	0.2	0.14	0.55	0.09	0.1	0.12	0.12	73.8%	39.6
1	Y	9	-1501.85	-0.05	0.11	-0.1	0.06	0.55	0.05	0.74	0.1	0.14	0.06	0.04	58.6%	48.8
1	Y	10	-821.94	-0.167	-0.141	-0.243	0.109	0.357	0.19	0.7	0.071	0.111	0.109	0.109	58.1%	43.2
1	Y	11	-749.34	-0.177	-0.177	-0.256	0.15	0.343	0.2	0.718	0.069	0.107	0.106	0.112	56.4%	44.1
1	Y	12	1700.92	-0.33	-1.28	-0.52	-0.1	0.2	0.36	0.37	0	0.07	0.24	0.19	31.6%	114.5
1	N	1	-602.725	0.031	-0.005	0.005	0.1	0.114	0.108	0.386	0.056	0.06	0.118	0.116	15.5%	121.1
1	N	2	-572.663	0.075	0.085	0.1	0.037	0.088	0.062	0.221	0.041	0.035	0.056	0.057	58.5%	29.1
1	N	3	-939.292	0.131	0.1	0.121	0.104	0.129	0.113	0.348	0.066	0.053	0.087	0.09	71.8%	34.1
1	N	4	-876.276	0.1	0.125	0.107	0.089	0.114	0.116	0.347	0.061	0.045	0.083	0.089	65.9%	32.1
1	N	5	-710.605	0.098	0.1	0.076	0.07	0.082	0.109	0.324	0.05	0.037	0.068	0.072	55.8%	37.96
1	N	6	-1034.72	0.12	0.13	0.11	0.14	0.12	0.12	0.43	0.07	0.05	0.1	0.1	56.0%	42.1
1	N	7	-1624.43	0.18	0.2	0.16	0.21	0.18	0.17	0.59	0.1	0.08	0.14	0.15	73.9%	41.14
1	N	8	-1941.71	0.2	0.24	0.17	0.23	0.2	0.18	0.65	0.11	0.09	0.16	0.16	71.0%	53.38
1	N	9	-1886.31	0.18	0.22	0.16	0.2	0.18	0.14	0.55	0.1	0.08	0.13	0.13	57.3%	61.81
1	N	10	-1813.39	0.21	0.15	0.18	0.25	0.21	0.19	0.7	0.12	0.1	0.15	0.15	62.9%	73.5
1	N	11	-1441.31	0.7	-1.19	0.5	0.73	-0.37	0.13	1.21	0.17	0.32	-0.19	-0.28	62.7%	61.73
1	N	12	886.548	-0.257	-0.493	-0.143	-0.14	0.024	0.033	0.089	-0.009	0.087	0.058	0.069	37.5%	54

Table 48. PLS Models w/ Validation for chair position 2, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
2	Y	1	17.9872	-0.0827	-0.2207	- 0.0906	0.0067	0.1046	0.0728	0.5461	0.0315	0.0791	0.0445	0.0434	57.4%	24.7
2	Y	2	-708.253	0.083	0.083	0.1	0.089	0.103	0.062	0.307	0.05	0.042	0.064	0.064	65.4%	28
2	Y	3	-759.792	0.062	0.1	0.059	-0.053	0.395	0.011	0.62	0.087	0.136	-0.026	-0.07	79.3%	23.55
2	Y	4	-970.301	0.1	0.132	0.106	0.124	0.143	0.113	0.412	0.071	0.057	0.093	0.094	84.2%	22.63
2	Y	5	-1007.2	0.12	0.14	0.11	0.12	0.14	0.11	0.4	0.07	0.06	0.09	0.09	77.1%	36.06
2	Y	6	-1272.32	0.13	0.16	0.12	0.17	0.16	0.14	0.46	0.08	0.07	0.11	0.12	72.2%	37.06
2	Y	7	-1586.46	-0.15	0.86	-0.38	0.47	0.48	0.09	-0.06	0.12	0.28	-0.12	0.08	78.1%	35.75
2	Y	8	-1628.57	-0.15	0.84	-0.45	0.39	0.4	0.11	-0.12	0.11	0.3	-0.08	0.14	78.4%	35.22
2	Y	9	-1630.18	0.11	0.13	0.09	0.16	0.18	0.12	0.52	0.08	0.07	0.1	0.11	65.4%	50.23
2	Y	10	-674.252	-0.009	0.418	-1.079	0.497	0.299	0.04	1.568	0.115	0.361	-2.501	2.252	57.6%	50..42
2	Y	11	-797.673	-0.256	0.425	-0.655	0.396	0.577	0.304	-0.687	0.038	0.24	-0.051	0.17	61.6%	41.55
2	Y	12	311.53	-0.178	-0.179	-0.089	0	0.108	-0.046	0.519	0.02	0.064	-0.011	-0.023	30.4%	35.67
2	N	1	-425.103	0.051	0.034	0.061	0.079	0.034	0.041	0.219	0.037	0.036	0.046	0.049	21.8%	75.63
2	N	2	-480.739	0.057	0.048	0.058	0.065	0.078	0.029	0.211	0.037	0.031	0.049	0.05	62.6%	25.89
2	N	3	-807.59	0.104	0.102	0.096	0.103	0.126	0.078	0.361	0.063	0.051	0.082	0.083	72.6%	28.07
2	N	4	-910.458	0.12	0.125	0.106	0.109	0.136	0.099	0.381	0.069	0.053	0.09	0.092	72.5%	29.64
2	N	5	-640.219	0.084	0.078	0.072	0.085	0.099	0.068	0.296	0.049	0.04	0.067	0.069	50.0%	34.07
2	N	6	-836.018	0.099	0.114	0.092	0.108	0.108	0.083	0.346	0.056	0.046	0.088	0.092	58.2%	34.09
2	N	7	-1352.47	0.16	0.16	0.15	0.17	0.14	0.15	0.49	0.09	0.07	0.13	0.14	45.9%	33.78
2	N	8	-2077.08	0.23	0.27	0.22	0.26	0.22	0.19	0.7	0.12	0.1	0.17	0.18	81.0%	45.88
2	N	9	-2023.37	0.2	0.22	0.19	0.26	0.21	0.17	0.68	0.11	0.09	0.14	0.15	68.1%	59.64
2	N	10	-1077.34	0.54	-0.62	0.14	0.75	-0.77	0.26	0.78	0.02	0.4	-0.11	-0.16	61.1%	55
2	N	11	-826.213	0.491	-0.593	0.142	0.417	-0.82	0.252	1.597	0.052	0.322	-0.133	-0.17	59.0%	48.31
2	N	12	-69.7545	0.0031	-0.0732	0.004	-0.0008	0.0521	0.0508	0.1639	0.016	0.0213	0.0418	0.044	18.7%	48.65

Table 49. PLS Models w/ Validation for chair position 3, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
3	Y	1	-301.539	0.02	0.007	0.018	0.059	0.049	0.047	0.193	0.024	0.027	0.038	0.038	56.5%	24.71
3	Y	2	-796.366	0.084	0.092	0.088	0.102	0.121	0.056	0.346	0.053	0.047	0.062	0.06	50.9%	43.53
3	Y	3	-839.253	0.106	0.104	0.103	0.096	0.129	0.089	0.363	0.06	0.05	0.082	0.083	73.6%	27.8
3	Y	4	-907.39	0.113	0.11	0.103	0.116	0.138	0.114	0.393	0.065	0.054	0.093	0.097	75.9%	27.76
3	Y	5	-1014	-0.18	0.27	0.38	0.28	0.36	0.14	0.27	-0.26	0.35	-0.37	0.41	83.2%	23.61
3	Y	6	-1022.95	0.11	0.14	0.11	0.14	0.13	0.1	0.39	0.07	0.06	0.09	0.1	76.6%	29.67
3	Y	7	-1579.01	-0.27	1.06	-0.26	0.49	0.29	0.4	-0.27	-0.03	0.32	-0.05	0.13	81.8%	32.43
3	Y	8	-1661.01	0.15	0.19	0.13	0.19	0.18	0.17	0.53	0.09	0.08	0.14	0.14	77.8%	41.64
3	Y	9	-1746.59	0.14	0.18	0.12	0.19	0.18	0.16	0.5	0.09	0.08	0.13	0.13	64.2%	52.13
3	Y	10	-1287.99	0.08	0.09	0.05	0.15	0.15	0.15	0.44	0.07	0.07	0.12	0.12	56.7%	55.67
3	Y	11	-1133.62	0.07	0.07	0.05	0.17	0.11	0.14	0.38	0.05	0.05	0.1	0.1	46.4%	60.33
3	Y	12	-580.032	0.041	-0.128	0.007	-0.182	0.164	0.104	0.658	0.075	0.088	0.145	0.153	42.7%	111.3
3	N	1	-354.073	0.046	0.027	0.053	0.065	0.04	0.034	0.193	0.028	0.028	0.031	0.031	26.2%	51.03
3	N	2	-241.843	-0.081	-0.259	-0.077	0.303	0.262	-0.114	0.683	0.038	0.112	0.02	0	40.9%	46.33
3	N	3	-635.913	-0.282	-0.016	0.534	0.283	0.27	-0.102	0.067	-0.273	0.377	-0.035	0.014	59.0%	31.11
3	N	4	-829.753	0.099	0.091	0.095	0.132	0.127	0.1	0.39	0.064	0.054	0.09	0.092	67.7%	32.43
3	N	5	-766.69	0.094	0.09	0.09	0.117	0.112	0.089	0.337	0.057	0.049	0.08	0.084	58.1%	35.54
3	N	6	-805.881	0.092	0.097	0.092	0.141	0.113	0.076	0.343	0.056	0.047	0.085	0.09	56.2%	37.89
3	N	7	-1089.79	-0.3	0.34	0.48	0.6	-0.08	-0.07	0.68	-0.32	0.36	-0.17	0.37	66.2%	34.16
3	N	8	-1636.67	0.19	0.23	0.18	0.22	0.16	0.17	0.54	0.1	0.07	0.13	0.14	76.2%	41.59
3	N	9	-2099.76	0.22	0.27	0.2	0.28	0.23	0.19	0.7	0.12	0.1	0.16	0.16	78.6%	51.39
3	N	10	-521.404	0.078	-0.237	0.119	0.799	-0.272	0.222	0.448	-0.03	0.075	-0.003	-0.004	36.5%	46.95
3	N	11	-498.151	0.067	0.031	0.065	0.111	0.061	0.067	0.24	0.04	0.037	0.05	0.049	28.4%	56.71
3	N	12	201.589	-0.217	-0.726	0.63	-0.202	-0.341	-0.06	0.869	-0.246	0.404	-0.28	0.283	30.0%	46.91

Table 50. PLS Models w/ Validation for chair position 4, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
4	Y	1	-463.476	0.033	-0.014	0.01	-0.039	0.12	0.071	0.395	0.051	0.058	0.083	0.089	41.7%	72.96
4	Y	2	-412.762	0.146	-0.159	0.162	-0.113	0.276	-0.128	0.046	-0.195	0.319	-0.196	0.214	56.7%	27.9
4	Y	3	-828.75	0.104	0.095	0.103	0.113	0.14	0.094	0.39	0.065	0.058	0.08	0.08	69.1%	37.44
4	Y	4	-976.066	0.12	0.122	0.114	0.132	0.152	0.105	0.446	0.071	0.06	0.092	0.093	80.6%	27.69
4	Y	5	-681.187	-0.014	-0.068	0.039	0.123	0.23	0.002	0.797	0.057	0.103	0.083	0.069	73.2%	28.91
4	Y	6	-1380.34	0.13	0.15	0.13	0.17	0.18	0.14	0.58	0.09	0.07	0.13	0.13	77.1%	37.71
4	Y	7	-1171.84	-0.04	-0.06	-0.01	0.15	0.28	0.07	1.08	0.08	0.13	0.17	0.14	76.9%	36.76
4	Y	8	-1261.59	-0.05	-0.02	-0.05	0.02	0.35	0.11	0.99	0.08	0.13	0.14	0.13	81.0%	31.03
4	Y	9	-1306.69	-0.08	-0.05	-0.07	-0.06	0.43	0	1.05	0.09	0.16	0.11	0.08	69.8%	40.14
4	Y	10	-646.534	-0.197	-0.288	-0.22	0.071	0.324	0.122	0.973	0.05	0.115	0.124	0.109	67.4%	33.72
4	Y	11	-611.382	-0.191	-0.291	-0.224	0.079	0.304	0.104	0.898	0.049	0.108	0.134	0.126	62.6%	35.26
4	Y	12	1634.11	-0.28	-0.96	-0.44	-0.47	-0.01	0.57	-0.01	-0.06	0.03	0.26	0.32	27.2%	90.89
4	N	1	-275.884	0.03	-0.015	0.026	0.075	0.046	0.057	0.238	0.03	0.037	0.031	0.032	26.4%	65.17
4	N	2	-195.974	-0.057	-0.166	-0.042	0.121	0.15	0.028	0.526	0.05	0.088	0.033	0.035	46.0%	34.49
4	N	3	-752.822	0.101	0.082	0.091	0.116	0.124	0.093	0.382	0.062	0.051	0.075	0.074	57.3%	37.91
4	N	4	-814.647	0.104	0.101	0.092	0.135	0.128	0.098	0.393	0.064	0.05	0.079	0.08	58.4%	36.88
4	N	5	-638.206	0.083	0.078	0.071	0.114	0.1	0.077	0.301	0.048	0.04	0.066	0.067	42.8%	39.98
4	N	6	-644.523	0.039	-0.108	0.02	0.331	0.122	-0.024	0.619	0.051	0.076	0.096	0.082	55.2%	36.85
4	N	7	-1298.92	0.16	0.15	0.16	0.17	0.13	0.13	0.48	0.08	0.06	0.11	0.11	66.6%	43.17
4	N	8	-1970.95	0.22	0.24	0.21	0.24	0.21	0.16	0.69	0.12	0.1	0.16	0.16	70.4%	58.52
4	N	9	-1956.11	0.2	0.19	0.19	0.23	0.2	0.13	0.64	0.11	0.1	0.14	0.14	62.3%	76.57
4	N	10	-1405.87	0.18	0.13	0.16	0.17	0.15	0.15	0.56	0.09	0.07	0.12	0.11	60.2%	57.26
4	N	11	-1333.93	0.18	0.15	0.16	0.11	0.14	0.14	0.56	0.08	0.07	0.11	0.11	50.1%	70.56
4	N	12	646.815	-0.216	-0.587	-0.172	0.059	0.118	0.112	0.357	0.023	0.102	0.066	0.067	29.4%	61.62

Table 51. PLS Models w/ Validation for chair position 5, with and without the harness.

Chair No,	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
5	Y	1	-237.459	0.009	-0.022	0.005	0.045	0.061	0.04	0.206	0.025	0.028	0.024	0.019	30.8%	36.37
5	Y	2	-488.304	0.045	0.026	0.039	0.091	0.074	0.053	0.282	0.039	0.037	0.049	0.048	50.8%	33.65
5	Y	3	-342.198	-0.045	-0.212	0.017	0.16	0.159	0.077	0.532	0.042	0.105	0.073	0.075	62.9%	34.95
5	Y	4	-587.233	-0.116	-0.255	0.37	0.303	0.148	0.25	-0.823	-0.137	0.435	-0.373	0.362	73.4%	28.72
5	Y	5	-870.618	0.106	0.122	0.088	0.124	0.107	0.153	0.432	0.06	0.047	0.088	0.096	47.7%	59.32
5	Y	6	-920.661	0.105	0.138	0.089	0.122	0.099	0.15	0.437	0.058	0.044	0.081	0.088	40.6%	73.17
5	Y	7	-1330.9	0.13	0.18	0.11	0.17	0.14	0.19	0.53	0.08	0.06	0.12	0.12	51.9%	71.19
5	Y	8	-1537.52	0.14	0.17	0.11	0.19	0.16	0.18	0.55	0.08	0.07	0.13	0.13	65.9%	53.21
5	Y	9	-1573.19	0.12	0.15	0.1	0.17	0.17	0.13	0.47	0.08	0.07	0.11	0.11	65.5%	48.59
5	Y	10	-670.758	-0.176	-0.218	-0.253	0.313	0.327	0.217	0.839	0.046	0.131	0.125	0.118	66.7%	42.42
5	Y	11	-1092.43	0.06	0.05	0.05	0.13	0.12	0.1	0.41	0.05	0.06	0.11	0.11	46.0%	64.82
5	Y	12	806.742	-0.16	-0.888	-0.272	-0.141	0.127	0.237	0.73	0.04	0.08	0.152	0.129	31.9%	75.46
5	N	1	-84.5835	-0.0359	-0.0531	0.0125	0.1277	0.0178	0.0175	0.2312	0.0259	0.0339	-0.0205	-0.0113	21.0%	54.03
5	N	2	-431.616	0.042	0.029	0.039	0.074	0.072	0.048	0.214	0.032	0.029	0.054	0.056	40.9%	29.82
5	N	3	-585.631	0.077	0.068	0.073	0.112	0.087	0.07	0.274	0.046	0.039	0.064	0.065	42.4%	38.61
5	N	4	-693.753	0.099	0.104	0.084	0.115	0.073	0.13	0.346	0.051	0.037	0.069	0.076	37.1%	60.23
5	N	5	-736.398	0.105	0.097	0.093	0.118	0.085	0.12	0.359	0.055	0.04	0.071	0.076	41.9%	51.75
5	N	6	-678.634	0.096	0.093	0.086	0.13	0.08	0.084	0.304	0.05	0.039	0.06	0.064	44.0%	44.24
5	N	7	-803.359	0.096	0.1	0.088	0.156	0.1	0.08	0.33	0.055	0.045	0.08	0.084	58.5%	36.65
5	N	8	-1340.82	0.16	0.18	0.15	0.18	0.15	0.12	0.44	0.08	0.06	0.12	0.13	73.5%	36.95
5	N	9	-1974.4	0.21	0.26	0.2	0.26	0.22	0.17	0.63	0.11	0.1	0.16	0.17	73.7%	56.48
5	N	10	-437.635	0.064	0.018	0.057	0.12	0.046	0.053	0.191	0.037	0.033	0.048	0.046	28.8%	58.57
5	N	11	-185.868	0.388	-1.361	0.454	0.362	-0.024	0.087	-1.905	0.113	0.4	-0.071	-0.188	35.7%	55.12
5	N	12	118.693	-0.093	-0.333	-0.07	0.041	0.142	0.022	0.627	0.034	0.066	0.049	0.038	28.1%	40.92

Table 52. PLS Models w/ Validation for chair position 6, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
6	Y	1	113.942	-0.107	-0.277	-0.116	0.116	0.104	0.1	0.531	0.027	0.08	0.015	0.006	43.6%	31.03
6	Y	2	-356.757	0.039	0.038	0.032	0.06	0.071	0.062	0.212	0.031	0.031	0.043	0.046	46.1%	32.05
6	Y	3	-667.259	0.09	0.083	0.086	0.128	0.098	0.087	0.298	0.055	0.047	0.066	0.066	44.9%	46.2
6	Y	4	-902.539	0.114	0.112	0.108	0.133	0.137	0.107	0.414	0.069	0.058	0.086	0.087	71.5%	32.94
6	Y	5	-979.813	-0.193	0.09	0.478	0.325	0.201	-0.042	1.083	-0.226	0.313	-0.159	0.137	76.3%	27.14
6	Y	6	-1327	0.14	0.15	0.14	0.16	0.16	0.13	0.54	0.08	0.07	0.12	0.12	72.2%	38.07
6	Y	7	-1613.4	0.15	0.17	0.14	0.18	0.19	0.14	0.61	0.09	0.08	0.13	0.13	72.3%	41.64
6	Y	8	-1666.39	0.14	0.16	0.13	0.15	0.18	0.12	0.57	0.09	0.07	0.12	0.12	71.1%	41.41
6	Y	9	-1758.86	0.13	0.13	0.13	0.14	0.18	0.11	0.57	0.08	0.07	0.11	0.11	63.9%	49.36
6	Y	10	-944.442	-0.113	-0.288	-0.109	-0.025	0.369	0.103	1.105	0.059	0.132	0.14	0.126	54.5%	50.6
6	Y	11	-807.178	-0.147	-0.339	-0.112	-0.052	0.401	0.033	1.199	0.053	0.127	0.144	0.128	49.6%	55.12
6	Y	12	1439.04	-0.18	-0.96	-0.43	-0.91	-0.14	0.85	0.09	0	0.14	0.26	0.32	23.2%	122.7
6	N	1	-598.939	0.103	0.089	0.088	0.034	0.041	0.096	0.224	0.047	0.043	0.035	0.041	21.8%	106.37
6	N	2	-122.096	-0.045	-0.245	-0.049	0.289	0.05	0.151	0.402	0.045	0.061	0.027	0.043	34.6%	40.84
6	N	3	-762.55	0.107	0.077	0.097	0.14	0.11	0.105	0.35	0.064	0.051	0.08	0.082	47.0%	50.42
6	N	4	-889.27	0.122	0.101	0.111	0.161	0.12	0.117	0.368	0.071	0.055	0.086	0.091	49.3%	53.46
6	N	5	-741.546	0.097	0.072	0.083	0.164	0.105	0.094	0.329	0.061	0.049	0.074	0.077	44.8%	52.68
6	N	6	-768.645	0.129	-0.279	0.107	0.729	-0.135	-0.034	0.716	0.117	0.112	-0.06	-0.018	53.1%	42.05
6	N	7	-1183.3	0.14	0.14	0.13	0.16	0.14	0.11	0.47	0.08	0.06	0.12	0.12	67.4%	37.17
6	N	8	-2033.16	0.23	0.26	0.22	0.23	0.23	0.19	0.74	0.12	0.1	0.17	0.17	78.1%	45.98
6	N	9	-2024.97	0.2	0.24	0.2	0.21	0.21	0.16	0.71	0.11	0.09	0.15	0.15	65.7%	59.31
6	N	10	-1766.51	0.21	0.19	0.21	0.18	0.23	0.15	0.74	0.11	0.09	0.15	0.14	52.7%	84.72
6	N	11	-1472.56	0.18	0.16	0.17	0.15	0.18	0.16	0.62	0.09	0.08	0.12	0.12	47.9%	78.52
6	N	12	702.825	-0.217	-0.449	-0.169	0.151	-0.079	0.079	0.288	0.034	0.066	0.024	0.041	14.7%	80.53

Table 53. PLS Models w/ Validation for chair position 7, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
7	Y	1	-171.359	-0.001	-0.016	-0.005	0.049	0.04	0.04	0.146	0.019	0.022	0.025	0.026	23.6%	35.08
7	Y	2	21.1755	-0.0904	-0.235	-0.0954	0.125	0.1411	0.0834	0.4805	0.0293	0.0683	0.038	0.041	41.3%	32.16
7	Y	3	-679.076	0.083	0.061	0.071	0.126	0.112	0.098	0.358	0.059	0.051	0.081	0.081	45.6%	46.05
7	Y	4	-849.1	0.11	0.091	0.094	0.146	0.125	0.108	0.405	0.069	0.056	0.093	0.095	61.0%	38.81
7	Y	5	-659.494	-0.002	-0.133	0.011	0.265	0.226	-0.028	0.686	0.086	0.112	0.075	0.074	68.1%	33.54
7	Y	6	-961.416	0.099	0.103	0.098	0.146	0.133	0.086	0.417	0.065	0.057	0.089	0.09	69.5%	35.42
7	Y	7	-1663.47	0.16	0.2	0.16	0.19	0.2	0.15	0.64	0.1	0.09	0.15	0.15	74.9%	47.23
7	Y	8	-1672.14	0.14	0.17	0.13	0.17	0.2	0.14	0.6	0.09	0.08	0.14	0.14	83.0%	35.81
7	Y	9	-1750.98	0.13	0.15	0.12	0.16	0.2	0.12	0.58	0.09	0.08	0.12	0.12	70.6%	46.27
7	Y	10	-1393.99	0.09	0.05	0.08	0.12	0.17	0.09	0.55	0.07	0.07	0.11	0.11	53.4%	57
7	Y	11	-1170.27	0.06	0.03	0.07	0.11	0.1	0.08	0.48	0.05	0.05	0.11	0.1	43.1%	70.34
7	Y	12	-237.475	0.033	-0.171	0.085	0.143	0.017	-0.046	0.481	0.038	0.044	0.03	0.015	17.2%	95.46
7	N	1	-149.154	0.012	-0.01	0.03	0.105	0.002	0.014	0.145	0.023	0.026	-0.01	-0.006	14.6%	65.21
7	N	2	-389.298	-0.039	-0.061	-0.02	0.18	0.129	0.079	0.467	0.042	0.052	0.084	0.09	40.5%	73.77
7	N	3	-580.201	0.075	0.05	0.072	0.138	0.089	0.081	0.264	0.051	0.044	0.071	0.074	39.7%	51.55
7	N	4	-612.23	0.084	0.058	0.082	0.127	0.088	0.096	0.311	0.051	0.045	0.068	0.07	45.0%	47.15
7	N	5	-620.847	0.084	0.054	0.078	0.125	0.106	0.077	0.324	0.051	0.047	0.061	0.062	39.6%	54.35
7	N	6	-322.519	-0.035	-0.312	0.01	0.4	0.191	-0.042	0.566	0.052	0.088	0.051	0.055	40.0%	48.59
7	N	7	-648.558	-0.014	-0.072	0.053	0.414	0.118	-0.099	0.557	0.047	0.077	0.085	0.084	46.9%	41.39
7	N	8	-1474.02	0.17	0.2	0.16	0.17	0.16	0.14	0.51	0.09	0.07	0.13	0.13	65.1%	43.51
7	N	9	-2029.91	0.22	0.27	0.21	0.23	0.22	0.17	0.69	0.12	0.09	0.16	0.16	70.7%	55.74
7	N	10	-659.439	0.075	0.059	0.079	0.075	0.101	0.074	0.323	0.045	0.042	0.07	0.07	41.0%	46.9
7	N	11	-666.974	0.084	0.057	0.085	0.082	0.1	0.078	0.295	0.046	0.044	0.072	0.071	40.1%	52.1
7	N	12	685.499	-0.222	-0.536	-0.139	0.054	0.057	0.122	0.429	0.008	0.084	0.036	0.035	32.5%	52.63

Table 54. PLS Models w/ Validation for chair position 8, with and without the harness.

Chair No.	Harness	Point	Constant	Sitting Height	Acromial Height Sitting	Eye Height Sitting	Buttock - Knee Length	Knee Height Sitting	Biacromial Breadth	Hand Length	Stature	Arm Span	Thumb Tip Reach	Radial Stylion	R^2	S
8	Y	1	188.278	-0.105	-0.465	-0.118	0.206	0.088	0.086	0.551	0.026	0.075	0.039	0.015	47.3%	33.05
8	Y	2	48.8628	-0.1019	-0.3091	-0.0583	-0.0106	0.1287	0.1473	0.5975	0.0022	0.0615	0.0999	0.0899	44.2%	36.71
8	Y	3	-166.984	-0.056	-0.286	-0.031	0.186	0.165	0.086	0.385	0.032	0.077	0.112	0.113	50.1%	37.42
8	Y	4	-387.345	0.001	-0.251	-0.002	0.23	0.149	0.153	0.348	0.07	0.102	0.087	0.088	60.9%	36.72
8	Y	5	-504.674	0.007	-0.209	0.027	0.231	0.195	0.057	0.604	0.066	0.117	0.057	0.048	68.1%	32.47
8	Y	6	-865.383	0.094	0.094	0.089	0.141	0.132	0.085	0.392	0.063	0.055	0.085	0.086	73.9%	30.71
8	Y	7	-1209.2	0.12	0.14	0.12	0.16	0.16	0.12	0.48	0.08	0.07	0.11	0.12	70.7%	37.12
8	Y	8	-1525.73	0.14	0.15	0.13	0.17	0.18	0.14	0.54	0.09	0.08	0.14	0.14	73.7%	38.27
8	Y	9	-1580.44	0.12	0.13	0.11	0.16	0.18	0.12	0.53	0.08	0.07	0.12	0.12	66.5%	45.54
8	Y	10	-803.198	-0.095	-0.206	-0.102	0.158	0.286	0.125	0.779	0.047	0.106	0.144	0.133	62.7%	38.67
8	Y	11	-655.373	-0.119	-0.233	-0.123	0.087	0.304	0.083	0.783	0.043	0.103	0.151	0.142	61.2%	37.46
8	Y	12	660.717	0.044	-1.167	0.304	-0.195	-0.194	0.322	1.31	-0.113	0.105	0.002	-0.008	36.4%	41.79
8	N	1	-117.153	-0.02	0.133	0.076	0.356	-0.137	0.113	0.053	0.016	0.016	-0.213	-0.16	20.1%	53.6
8	N	2	-181.019	0.007	0.003	0.01	0.061	0.029	0.025	0.164	0.019	0.017	0.031	0.033	29.1%	33.59
8	N	3	-366.169	0.046	0.03	0.054	0.093	0.071	0.052	0.212	0.034	0.033	0.042	0.043	33.5%	45.85
8	N	4	-645.032	0.085	0.077	0.087	0.135	0.083	0.094	0.3	0.056	0.047	0.068	0.072	49.0%	49.36
8	N	5	-713.162	0.095	0.082	0.095	0.146	0.094	0.081	0.312	0.06	0.052	0.07	0.074	48.7%	54.1
8	N	6	-657.532	0.087	0.057	0.085	0.154	0.089	0.062	0.315	0.057	0.045	0.068	0.071	44.9%	51.17
8	N	7	-553.609	-0.015	-0.271	0.044	0.588	0.06	-0.06	0.658	0.081	0.101	0.04	0.044	52.0%	42.25
8	N	8	-996.74	0.114	0.123	0.113	0.145	0.127	0.101	0.416	0.066	0.054	0.088	0.088	61.5%	36.98
8	N	9	-1833.55	0.2	0.23	0.2	0.21	0.21	0.18	0.66	0.11	0.09	0.16	0.16	75.2%	45.9
8	N	10	-456.151	0.066	0.026	0.062	0.102	0.051	0.066	0.215	0.039	0.034	0.048	0.048	25.0%	60.07
8	N	11	-354.359	0.053	-0.008	0.052	0.098	0.064	0.052	0.185	0.037	0.035	0.041	0.038	27.3%	65.54
8	N	12	508.963	-0.166	-0.425	-0.108	0.011	0.046	0.031	0.554	0.003	0.052	0.059	0.048	29.8%	40.96