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ASSESSING THE ACCURACY OF PEAK AND CUMULATIVE LOW BACK ANALYSES WHEN HUMAN ANTHROPOMETRY IS SCALED IN A VIRTUAL ENVIRONMENT

by
Christina Godin

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ABSTRACT

ASSESSING THE ACCURACY OF PEAK AND CUMULATIVE LOW BACK ANALYSES WHEN HUMAN ANTHROPOMETRY IS SCALED IN A VIRTUAL ENVIRONMENT

Christina Godin
University of Windsor

This study addressed the effect of scaling subjects in a virtual reality environment when performing ergonomic evaluations for assembly automotive tasks. Ten male and ten female automotive employees participated in this study. Subjects were selected to fit into one of 4 anthropometric groups (n=5/group); 5^{th} percentile female (5F), 50^{th} percentile female (50F), 50^{th} percentile male (50M), or 95^{th} percentile male (95M). Each subject was asked to perform 3 automotive assembly tasks while interacting with a digital rendering of a vehicle in virtual reality. The subjects were represented in virtual reality as a human manikin (Classic Jack, UGS) whose actions were driven by their actual motions captured via motion tracking (EvaRT, MotionAnalysis). Each subject performed the tasks under 4 different conditions; in one condition, the subject appeared as their true size, and in the three other conditions, they were scaled to appear as the size of the other three subject groups. Peak and cumulative low back loads, joint angles at the point of peak compression and peak and cumulative resultant shoulder moments were output from the Task Analysis Tool Kit within Classic Jack. A Repeated Measures ANOVA with a Tukey's significance post hoc test were used to identify differences within the data ($p<0.05$). Results show that, for virtual assessments of peak and cumulative low back compression, scaling subjects between the range of the 50F to the 95M was deemed an acceptable practice. In terms of ergonomic assessments related to the shoulder, if limits are to be based on 5F or 50F individuals, subjects can be scaled anywhere within the

range of 5F to 50F, without affecting the accuracy of the results and subsequent ergonomic decisions. If results will be based on 50M or 95M, it is acceptable to select subjects that fall within this range and scale them to the desired size. These recommendations are based on tasks typical of automotive assembly type tasks and are intended to act as a guideline when selecting subjects for ergonomic studies performed with motion capture and virtual reality integration.

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LIST OF ABBREVIATIONS

LBP – Low Back Pain
AL – Action Limit
N - Newton
NIOSH – National Institute of Occupational Health and Safety
3DSSPP – Three Dimensional Static Strength Posture Prediction Program
SA – Scaled Anthropometry
TA – True Anthropometry
TLV – Threshold Limit Value
LI – Lifting Index
JSI – Job Severity Index
Kg - Kilograms
L4/L5 – Lumbar Level 4 / Lumbar Level 5
3D – Three Dimensional
Hz - Hertz
MN*s – Mega Newton Seconds
2D – Two Dimensional
PC – Personal Computer
VEMO – Variable In-and Egress Mock-up
VOPP - Vehicle Operations Pilot Plant
Cm – Centimetre
WCHS – Work Center for Human Simulation
Ghz – Gigahertz
Fps – Frames per Second
Mm – millimetres
TAT – Task Analysis Toolkit
ANOVA – Analysis of Variance
5F – 5th Percentile Female
50F – 50th Percentile Female
50M – 50th Percentile Male
95M – 95th Percentile Male

I. INTRODUCTION

BACKGROUND

Several large manufacturing companies, in particular those producing vehicles of transport, such as automotive, aviation, and agricultural equipment have migrated towards the use of digitally created environments to test new vehicle design. This is particularly common in the field of ergonomics where, simulated humans can perform tasks in a computer environment to predict the risk of injury. The use of computer simulation is believed to reduce cost to a company as fewer physical prototypes are required, thereby saving money in terms of time, materials and manpower. In the field of ergonomics, virtual environments have been used to assess vehicle design from the occupant's (driver's) perspective (Rigel, Assmann & Bubb, 2003; Dai, Teng, & Oriet, 2003; Blome, Dukic, Hanson & Hogberg, 2003), however very little has been done in terms of assessing the worker who must assemble the product. From an ergonomic point of view, the opportunity to assess a job virtually, in order to determine the risk of injury, is a great advantage. The risk of injury can be assessed and eliminated, or reduced, before ever requiring a true human to perform the task. The limitation of this approach, however, is that a digital human cannot always accurately predict the movement patterns of a true human and, therefore, the strategy used by a virtual human may not truly represent what is done in real life (Doi & Haslegrave, 2003; Reed, Parkinson, & Klinkenberger, 2003). In order to combat this problem, companies are beginning to invest in Motion Capture equipment. This allows a real human to perform a task while viewing a virtual environment through a head mounted visual display unit or wall projected image. This approach allows the cost savings of creating a digital environment rather then a physical prototype, but also ensures the task is executed realistically by a true human.

Typically, engineers will design a product or workstation to accommodate the extremes of a population, being the smallest female to the largest male (Feyen, Liu, Chaffin, Jimmerson & Joseph, 2000). In a virtual environment, you have the option of taking a person of any stature and scaling the environment around them such that they appear to match the anthropometry that is desired for testing. For example, a large male could be scaled to represent a small female while performing an activity. While it is common practice, among manufacturers currently employing motion capture analyses, to alter the anthropometric measures of their subjects, it remains unknown if this practice produces the same results as would be obtained from using a person who is truly the desired size. Of particular interest, is the effect that human scaling has on estimating the risk of low back injury, as this has been one of the most common and significant occupational problems experienced by workforces worldwide (Hagen & Thune, 1998; Clemon, 2002; Punnett, Fine, Keyserling, Herrin & Chaffin, 1991; Kumar, 1990; Norman, Wells, Frank, Shannon & Kerr, 1998). For example, European workers affected by back pain had a median value of 43 work absences over a 1 year period (Hagen & Thune, 1998). In the United States' manufacturing industry, 23% of all injuries occurring in 1995 affected the low back (Mital, Pennathur & Kansal, 1999a). Furthermore, compensation costs were highest for the back compared with all other regions of the body and 26% of all those injured lost 21 days or more of work (Mital, Pennathur & Kansal,, 1999b). Ontario statistics reveal that back injuries result in the greatest number of lost time claims relative to any other affected area of the body, at 29.6% (WSIB Statistical

Supplement, 2002). Overexertion was reported as a primary cause, which includes activities such as lifting, pushing and pulling objects.

The alarming occurrence, and resultant costs, of low back pain (LBP) among workers demonstrates the necessity of reducing risk factors associated with this disorder. Considerable research has been dedicated to reducing occupational back pain, and numerous risk factors are cited in the literature highlighting the multifactorical etiology of this disorder. Psychosocial factors, such as job satisfaction, coworker support, and workplace social environment prove to be significant when assessing occupational low back pain (Kerr, Frank, Shannon, Norman, Wells, Neumann, Bombardier & the Ontario Back Pain Study Group, 2001, Bigos, Battie, Spengler, Fisher, Fordyce, Hansson, Nachemson & Wortley, 1991). Recent research has shown that it is not only time spent on the job, but also non-occupational activities (ex: cooking, cleaning) that can affect an individual during their work hours (Godin, Andrews & Callaghan, 2003; Azar, Andrews & Callaghan, 2003; Lauder, Andrews & Callaghan, 2002). For example, peak spine loads produced during non-occupational tasks have been shown to exceed the NIOSH (National Institute of Occupational Safety and Health) Action Limit (AL) of 3400 N (Godin et al., 2003).

Biomechanical factors, such as peak and cumulative loads, along with the postural considerations of a task, have also been identified as risk factors for work-related low back pain. Punnett et al. (1991) showed that trunk posture, independent of the force characteristics of a task, was associated with reporting of low back pain in an automotive industrial setting. The National Institute of Occupational Safety and Health (NIOSH) assessed the effects of peak loads on the spinal structures, and suggested that any lifting scenario causing a peak spine compression greater then 3400 N is associated with negative implications for the lifter (NIOSH, 1981). Other thresholds have also been suggested, for example, by Mital, Nicholson & Ayoub (1993) (2700 N for females, 3900 N for males), however, the common goal of all current limits is to reduce the risk of injury resulting from peak spinal loads. Such threshold values are commonly used to assess biomechanical risk factors in occupational settings. Despite this, low pack pain continues to persist.

Recent efforts have shown that cumulative loads are associated with low back disorders in work settings (Kumar, 1990; Norman, et al., 1998; Jager, Jordan, Luttmann & Laurig, 2000; Daynard, Yassi, Cooper, Tate, Norman & Wells, 2001, Seilder, Bolm-Audorff, Heiskel, Henkel, Roth-Kuver, Kaiser, Bickeboller, Willingstorfer, Beck, & Elsner, 2001). Evidence from an epidemiological perspective has been reported by Kumar (1990), Norman et al. (1998) and Siedler et al. (2001). Kumar (1990) found that cumulative compression and shear forces were significantly higher in institutional aides with pain compared to those without pain. Automobile assembly workers who experienced pain have also been shown to have higher cumulative load values when compared with their pain free counterparts (Norman, et al., 1998). These studies suggest that exposure to cumulative load predisposes the spine to pain and/or injury and thus is a risk factor for low back disorders. Furthermore, using a blinded case-control design, German researchers Seidler et al. (2001) identified a link between cumulative physical work and lumbar spine disease, in particular osteochondrosis and spondylosis. While there is no current threshold value for cumulative low back loads, the above evidence suggests that it is an important occupational risk factor and should be considered during the design or assessment of a job.

Virtual ergonomics is a rapidly emerging technology that is used to make proactive workplace decisions and correct potentially injurious products while they are still being designed. Given the impact of low back pain among today's workforce, the opportunity to address injury risk during the design phase offers a promising solution to one of the most pressing ergonomic concerns in industry. However, in order to be truly effective, it is imperative that a virtual assessment closely reflects the true life scenario. One of the greatest advances in making virtual ergonomics more representative of the actual job or task being analyzed, was incorporating the use of motion capture in order to simulate true human actions. Thus, low back assessments can be generated using the postural information of an actual person, rather than a human model. The typical protocol employed in motion capture labs today is to scale the dimensions of a test subject in order to represent a specific set of anthropometrics (for example, a small female) while that individual interacts in the virtual environment. The movements of this person are then utilized to assess the moments and forces acting on the low back and, ultimately, allow for a decision to be made about the associated injury risk. This procedure is quite sophisticated, when contrasted with the typical reactive video-based or observational methods of generating postural information for entry into assessment tools. It is even more advanced when compared to relying on user's predictions of a human model's movements or posture. What remains unknown, however, is whether or not it is valid to make the person performing in motion capture appear larger or smaller than they truly are in order to represent a desired population (for example a small female) when generating a low back assessment. Thus, the question remains, can humans be scaled using motion capture to appear differently in a virtual environment and be expected to act or move the same as the size of person that they have been scaled to represent? In order to ensure an accurate measure of the peak and cumulative loads on the low back during a virtual assessment, it is imperative that sound procedures are available for scaling subjects during a motion capture session to ensure valid results.

STATEMENT OF THE PURPOSE

The primary goal of this study was to define the parameters for scaling human anthropometry in a virtual environment. More specifically, this study addressed the validity of using different sized subjects in a virtual environment when the anthropometric criteria in question are different than that of the subject performing the task(s). For example, the study was designed to determine if a 5th percentile female would produce similar peak and cumulative low back compression as a larger subject that was scaled to appear as a 5th percentile female. There were four groups of subjects in this study, 5th percentile females, 50th percentile females, 50th percentile males, and 95th percentile males. Each subject was asked to perform a series of tasks in a motion capture lab. One time, the subject appeared as their true size, and the three additional times, they were scaled to appear as the size of the other three subject groups. Prior to this study, it is assumed that similar results would be obtained with any sized person being scaled to any particular size of interest and expensive decisions were made based on this assumption. Subjects were asked to perform a series of tasks in a motion capture lab and these motions were linked to a computer software to produce a frame-by-frame analysis of the peak and cumulative compression values for each task.

HYPOTHESES

1. When a small female is scaled to represent a large male, significant differences ($p<0.05$) will exist in the results of a peak and cumulative low back compression assessment. The same will hold true when a large male is scaled to represent a small female.

Given the large inherent differences in terms of muscle size, overall body mass and height between a true 5th percentile female and a 95th percentile male scaled down to a tiny woman, the large male is expected to utilize a different movement strategy than a small woman. Since the larger male will automatically generate higher absolute compressive forces on the low back, due to the internal forces generated by body weight and longer moment arms, his movements are expected to reflect a strategy that generates the least demands on the body, regardless of external factors. Thus, where the small female may choose to use one of several possible strategies to achieve a goal, the large male, scaled down in size, may be limited by his true body dimensions (due to the greater strength demand of the higher segment masses), and therefore may not be as flexible in adopting new or variable movement strategies as may be expected for the smaller female, regardless of how small he appears in the virtual environment.

2. No significant differences ($p<0.05$) will be observed in the results of a low back assessment of peak and cumulative compression between the 5th percentile female and the 50th percentile female when they are scaled to represent one another. The same is expected for the 50th percentile male and the 95th percentile male.

Given all possible scaling scenarios, the difference in body size is least when scaling between an average male or female and a small female or large male. Thus, for example, it is anticipated that during conditions where the environment of the 50th percentile person is being utilized, scaled subjects (5th female and 95th male) will choose movement patterns that are similar to the un-scaled 50th percentile person. This is because the changes made to the environment when scaling between the average person and the 5th female or 95th male are less than when scaling between the extremes of a population (small female to large male). Therefore, it is more likely that smaller adjustments in anthropometry (for example; 5th to 50th rather than 5th to 95th) will result in subjects performing similar to how they would in their un-scaled environment.

3. Differences between conditions and subjects will be lower for low back cumulative compressive forces than for peak forces.

Rectangular integration incorporates all frames of data across a time period, which includes both high and low compressive forces at any particular moment. Peak forces, on the other hand are based on one instant in time, where the highest compressive load is seen, and this value reflects what is happening at one frame within several thousands of frames collected during a trial. It is anticipated that calculating the sum of several frames will not be as sensitive to variability within the data, given that one subject may experience one high compressive loading instant followed by two low instants, while another may experience three instants of moderate-loading and both scenarios could potentially add up to the same magnitude.

II. LITERATURE REVIEW

THE AUTOMOTIVE INDUSTRY

In Canada alone, the manufacturing industry employs over six hundred thousand individuals which is the third largest employing sector, after health care and specialized trades (Statistics Canada, 2002). Manually laborious and repetitive tasks are common in automotive manufacturing and consist of non-neutral trunk postures such as bending, twisting, and manual material handling. These risk factors result in frequent and large cumulative and peak forces on the spine, which can ultimately lead to tissue injury (Punnett, et al., 1991; Norman et al., 1998). In fact, the automotive industry accounted for 9.6% of all injury claims in Canada in 2002, with the back being the most problematic area (WSIB Statistical Supplement, 2002). An effort to reduce the number of injuries is imperative, not only for the health and safety of the individual, but also due to the alarming cost associated with such injuries. In the United States, it is estimated that one quarter of the working population experiences low back pain, translating to an annual medical cost of 24 billion dollars (Frymoyer and Cats-Baril, 1991). Clearly, the low back remains an area of concern for both automotive workers and employers and requires further investigation in order to reduce the risk associated with this type of employment.

Numerous efforts have been made in the past to reduce the risk of low back injury among this workforce. In 1981, the risk associated with lifting was addressed by the National Institute for Occupational Health and Safety (NIOSH), who proposed a threshold for peak compression of 3400 N (NIOSH, 1981). The development of this guideline has led to subsequent threshold values (for examples see Mital et al., 1993;

Jager & Luttmann, 1991), which can be employed by Ergonomists in manufacturing environments to reduce the risk factors that contribute to high spinal compressive forces.

Norman et al. (1998) identified that both peak and cumulative forces were greater for auto workers who reported low back pain than for those who did not. In addition to studying the kinetic risk factors associated with work activities, others have looked at postural requirements in the automotive industry. Punnett et al. (1991) assessed the frequency of assuming non-neutral trunk postures for assembly employees and found that bending and twisting of the trunk is common in this environment. Specifically, workers who reported pain were found to spend a significantly greater percentage of their work cycle with the trunk in mild flexion (12.8 % versus 9.7%) and severe flexion (7.4% versus 4.1%) than workers who did not report back pain. As well, it was identified that the risk of injury, resulting from postural stresses, such as trunk flexion, axial twist and lateral bending, is 4 times greater than for tasks that require lifting a 44.5 N load once per minute, in any posture.

RECOMMENDED THRESHOLD LIMIT VALUES FOR PEAK SPINAL COMPRESSION

Peak spine compression has been consistently used as a criterion variable when assessing injury risk to the low back. Considerable research has been dedicated to determining threshold limit values (TLV) and developing tools to assess this risk factor. In 1981 the National Institute of Occupational Health and Safety (NIOSH) proposed lifting guidelines that were derived by integrating the principles of biomechanics, psychophysics and physiology. The biomechanical criterion is based on 2 compression limits; an Action Limit (AL) of 3400 N of peak spinal compression was proposed as the value that lifting tasks should not exceed if injury risk is to be minimized and 6400 N of peak compression was determined to be the value at which the risk of low back injury is significantly increased. The 1981 NIOSH lifting equation is limited, however, in that it only permits the analysis of sagittal plane lifting tasks. In order to broaden the scope of this equation, NIOSH assembled a team of experts to review the literature and re-evaluate the original lifting equation. The result of this effort was a revised formula which utilizes a Lifting Index (LI) to define the risk of injury. For lifts limited by the biomechanical criterion (low frequency lifting), the LI is still based around the 3400N peak compression threshold, and is a ratio of the load lifted relative to the recommended limit. However, the revised 1991 equation provides a method to assess lifting outside of the sagittal plane, and is believed to protect a greater number of workers from the risk of low back pain. At the time, the literature related to asymmetrical lifting was limited, however, it all supported a decrease in capacity when lifting outside of the sagittal plane. For example, when synthesizing the psychophysical evidence a decrease in maximum lifting capacity between 8 and 22% was noted, as well as a decrease in maximum isometric strength of 39%. Using this information, the NIOSH committee recommended a 30% decrease in the allowable weight of a lift where axial twisting of 90 degrees is observed. The degree of asymmetry can be calculated as the angle between the sagittal plane and the plane of asymmetry (which is the vertical plane intersecting the center of the ankles and the center of the hands) The NIOSH lifting equation remains a popular risk assessment tool for Ergonomists and is used in a variety of industrial settings.

In their guide to *Manual Material Handling*, Mital, Nicholson & Ayoub (1993) also suggest peak compression limits for the spine. It is suggested that peak low back compressive forces should not exceed 3930 N for males and 2689 N for females. The rational used to derive these values is based on injury statistics for low back disorders and a job severity index (JSI) that had been previously reported in the literature. In 1983, Ayoub proposed a lifting index which accounts for the size of a load, lifting frequency, and duration of work (as cited in Mital et al 1993). It was found that a JSI score ≥1.5 substantially increased low back injury rates. The maximum load that could be lifted by males at a JSI value of 1.5 was 27 kg, which translates to a peak compressive force of 3930N on the low back (Mital et al, 1993). This value represents approximately 70% of the maximum compressive strength of the spine (3900 N for females, 5700 N for males), proposed by Jager and Luttmann (1991). If the same rational is applied to females, then a maximum lifting load of 20 kg, or 2689 N, is permissible (Mital et al, 1993).

THE INTERACTIONS OF PEAK AND CUMULATIVE COMPRESSIVE LOW BACK LOADS IN THE WORK SETTINGS

The availability of guidelines for peak low back loading has allowed Ergonomists in a variety of work settings to reduce the risk factors which contribute to high peak compressive forces on the spine. Typically, this would include redesigning a workstation to improve postures, limiting the frequency of lifting, as well as reducing the weight of loads that are manipulated. A method for lowering the peak compressive demands on the low back was tested in a health care setting where patients must be handled manually (Daynard et al., 2001). A group of researchers assessed the effects of installing mechanical hoists and other lift assists for use during patient transfers. A number of patient handling activities, both with and without assists, and using various transfer methods, including 1 and 2 person manual lifts, transfer belts and mechanical hoists, were observed among nursing assistant personnel. Peak spine loads at L4/L5 were generally quite low (for example; bed to wheelchair transfer with device, 2010N), particularly with the use of assistive equipment, however, cumulative loads were found to increase under these conditions.

The use of a lift assist is generally known to increase the time requirements of a task, as the patient or item being maneuvered has to be placed securely into the device and the time needed to navigate the device from a start point to the end point is greater than with manual lifting. Given that the current method for calculating loads is through a linear summation over the entire time period, cumulative loads will become greater in magnitude as the length of a task increases. Thus, even though high peak low back loads can be remedied in this fashion, the potential of introducing other risk factors that can impact cumulative loading must be considered. This type of scenario offers a possible explanation for why low back disorders continue to persist despite efforts to reduce peak loading.

EVIDENCE OF CUMULATIVE LOADS AS A RISK FACTOR FOR LOW BACK PAIN AND INJURY

Epidemiological studies in occupational settings are particularly valuable when developing exposure guidelines. One such effort has addressed spinal injuries and the cumulative physical work for several occupations, including those found in the service and technology industries, a breadth of production related fields, as well as agriculture and mining (Seidler et al., 2001). The study was conducted in Germany and included 229 cases and 197 controls. Interviews were conducted to obtain estimates of physical work-load, assessing variables such as lifting, carrying, trunk posture, exposure to vibration, as well as non-occupational factors. Spine injures reported by cases in this study were osteochondrosis, spondylosis, and lumbar disc herniation, The Mainz-Dortmund dose model was used to calculate lumbar disc compression force by means of a 2-dimensional regression-based equation. When the sum of the forces on the lumbar spine was calculated for both cases and controls, it was clearly shown that cumulative compressive exposure is linked with lumbar spine disease.

Epidemiological research conducted among the North American working population has also shown a positive association between cumulative loads and low back pain (Kumar, 1990, Norman et al., 1998). In 1990, the prevalence of back pain and cumulative loading was observed among Canadian institutional aides (Kumar, 1990). A total of 161 participants completed a pain profile and questionnaire to collect information on both personal and work histories as well as current on-the-job risk factors such as type, intensity and duration of various work tasks. Participants were asked to describe the postural requirements of the job by manipulating a 3D manikin or by acting out the job. These postures, along with any associated hand loads, were recorded by the investigator and later input to a static biomechanical model. Static or sustained postures were calculated by multiplying the compressive and shear forces by the length of time the posture was sustained. For dynamic actions, a start and end posture were identified and the movements in between were assumed to be smooth and continuous. A compressive and shear force was calculated every 200 msec. (5Hz) for dynamic tasks and summed to determine the cumulative load for that activity. Results showed an average of 15.6 MN*s of cumulative compression and 2.5 MN*s of cumulative shear for the male group with pain, versus 6.6 MN*s of cumulative compression and 1.0 MN*s of cumulative shear for males without pain. Thus, the pain group had cumulative compression and shear forces that were an average of 136% and 150% higher, respectively, than the group without pain. These results, however, must be considered with caution, as the loads calculated were heavily dependant on the subject's ability to recall and communicate the demands of his or her job to the researcher. Furthermore, the researcher's interpretation of the postures described would have also had an impact on the results. In addition, the use of a paper and pencil method of data collection forced the researcher to make assumptions and interpolate data between the start and end points of dynamic activities, as opposed to knowing the true postural information throughout the entire activity.

Using a case-control design, Norman et al. (1998) looked at how various risk factors (peak and cumulative spine loads, trunk kinematics and hand loads) were related to the reporting of low back pain in the automotive industry. Participants (cases=104, controls=130) completed a detailed interview, providing relevant demographic, psychosocial and clinical information. As well, biomechanical measures were taken over a two-year period using a video-based posture analysis system and a 2D, quasi-dynamic biomechanical model. Cumulative loads of interest in this study were L4/L5 cumulative compression and shear forces as well as moments. These quantities were calculated by multiplying each of the task peaks by the duration of exposure for each task, and then multiplying the number of times the task was performed over a work shift. The total, or integrated exposure, was determined by summing together the exposure for each of the separate tasks. The shift exposure (dose) was higher for cases than controls on all cumulative variables. For example, the cumulative compression for cases and controls was 21 MN*s and 19.5 MN*s, respectively. Perhaps more importantly, is the fact that two cumulative variables: 1) integrated lumbar moment over the duration of the shift (OR for Inter-quartile spread = 1.4) and 2) the time averaged hand force (OR for Inter-quartile spread = 1.7), emerged as independent risk factors for low back pain reporting. Two other variables were also identified as independent risk factors in this study: 1) peak lumbar shear force and 2) peak torso flexion velocity. However this finding is not intriguing, given that peak low back loading has long since been established as a risk factor for low back pain and injury. Perhaps one of the most significant findings in this study is that cumulative variables, independent of all other factors, can be associated with low back pain. This affirms the need to consider cumulative risk factors in addition to the traditional variables addressed in a biomechanical or ergonomic assessment. According to the authors, this study was limited in terms of the reportedly weak criteria used to classify cases and controls, the use of 2D versus a more accurate 3D biomechanical model, and using a quasi-dynamic approach rather than full dynamics. As well, the methods used to calculate cumulative low back loads have been shown to result in an overestimation of exposure, given that the cumulative sum is based on the peak loads observed for each sub-task, rather than a point by point estimation of loading throughout an activity (Callaghan, Salewytsch & Andrews, 2001). Despite these limitations, Norman et al. (1998) demonstrated that cumulative loading was an independent risk factor for reporting low back pain.

CALCULATING CUMULATIVE LOAD

Data of an epidemiological nature is particularly important for addressing cumulative spine loads and their relationship with low back pain. However, this type of study requires a sizeable commitment on behalf of the research team, as efforts to gather and process large amounts of data can be daunting. While current endeavors continue to pursue optimal methods for the collection and processing of cumulative load data, considerable progress has been made, offering practical options for studying the effects of cumulative spine loads in work settings.

Cumulative load documentation presents the challenge of recording and quantifying a variation of spinal loads (ex. compression and shear forces as well as moments) with respect to time. To date, studies that have assessed cumulative low back loading have all used different assessment techniques. This hinders comparison of values between studies and ultimately limits progression towards a threshold limit value.

METHODS FOR ESTIMATING CUMULATIVE SPINAL LOADING

As noted, the methods used to calculate cumulative load have varied in the past. Norman et al. (1998) and Daynard et al. (2001) both used peak static loads calculated for a task and multiplied this value by the task time. This "square method" is particularly useful in reducing the time requirements of data processing. Alternatively, rectangular integration of the load time-histories has been frequently employed for quantifying cumulative low back loads (Kumar, 1990; Godin et al., 2003; Azar et al., 2003). Callaghan et al. (2001) compared five commonly used cumulative loading quantification methods to the 'gold standard' (rectangular integration of 30 Hz video) and determined the relative error for each method. The 5 methods tested were; 1) rectangular integration with a reduced sampling rate of 5Hz, 2) multiplication of the spinal loads at the initiation of the lift by the duration of the task (square), 3) division of the cycle into work and rest where: a) during work time the forces and moments at the beginning of the lift were multiplied by the time of the lift and b) during rest, the moments and forces associated with upright standing were multiplied by the length of the rest time. 4) accounting only for the work portion of the cycle, where rest time is not factored into the total cumulative load and 5) each cycle was divided into four main actions (get, lift, place, return load), and a cumulative load for each was determined by multiplying the loads for a representative posture in each action by the time of the action and then summing the results of all four actions together. It was found that even when reducing the sampling rate to 5 Hz for integration, the error associated with this method was considerably lower than for all other techniques. In fact, the average error reported for a 5Hz analysis was no greater than 6% for any trial. With error as high as 70%, the square method proved to be the least accurate estimate of cumulative loads relative to the 30 Hz analysis (Callaghan, et al., 2001). These results call into question the results of past studies which have employed a representative posture to quantify cumulative loads. As well, it highlights the difficulty in comparing quantities from study to study as the range of error between methods is so great. While the analysis by Callaghan et al. (2001) only incorporated sagittal plane lifting tasks, and thus may not reflect the true nature of some occupational activities, it nevertheless identifies an important methodological concern in the documentation of cumulative loads.

DOCUMENTATION TECHNIQUES AND DATA REDUCTION EFFORTS

Video has been the primary tool used to document cumulative loads, but it is very time consuming for both data collection and analysis. Godin et al. (2003) estimated that, even by reducing the sampling rate to 3Hz and using short video clips to represent longer time periods, 2 hours of video required approximately 25-30 hours of analysis. Research efforts have addressed this concern by reducing the time requirements for cumulative load documentation. Posture sampling approaches (ex. Kumar, 1990; Callaghan, Jackson, Albert, Andrews & Potvin, 2003) eliminate the need for video digitization. As well, in an analysis of sagittal plane, static lifting tasks Andrews and Callaghan (2003) showed that using a 3 Hz analysis of video provided estimates of cumulative low back loads (compression, reaction and joint shear forces as well as moments) with less than 5% error in the majority of cases relative to those estimated at 60 frames/second. A reduction in the time requirements and ultimately the cost of cumulative load documentation makes such endeavors more attractive for researchers. Given that considerable data are required for the development of a guideline for cumulative load exposure, data reduction efforts are paramount.

Azar et al. (2003) looked at using 2 types of self-report questionnaires, a logbook and a 2-hour recall, as an alternative to video documentation. Type, frequency and duration information was reported by participants while they performed two hours of simulated non-occupational tasks. Cumulative loads were generated from an estimated load for each activity multiplied by the time and frequency reported by each subject. This data was compared against joint coordinate data collected using an ARIEL (ARIEL Technologies Inc.) motion capture system that was input into a 2-dimensional, quasi-static biomechanical model, GOBER (University of Guelph, Guelph, Ontario, Canada). Results suggest that the logbook is a promising and simple method for documenting low back cumulative loads, as the estimated and actual cumulative moments were highly correlated ($r=0.989$, $p< 0.001$). However, before such a tool can be used widespread, it must be tested in occupational settings for further validation.

Using a magnetic tracking device, Agnew, Andrews, Potvin & Callaghan (2003) developed a method to instantaneously estimate cumulative loads without video. Real-time documentation using the magnetic tracking device provided extremely accurate results compared with a traditional 2D Static Biomechanical Model (GOBER, University of Waterloo, Waterloo, Ontario, Canada). The use of magnetic tracking devices requires an environment free of magnetic interference, thus making most industrial settings unsuitable. Nevertheless, in an effort to reduce the risk of injury before a job is ever performed on the plant floor, several companies are migrating towards a proactive approach for ergonomics, where the testing of a product or workstation occurs in a lab setting before ever bringing it to the factory. As such, the use of magnetic and also optical motion capture devices offers an accurate and efficient collection method for such applications.

ERGONOMICS AND VIRTUAL REALITY

The field of ergonomics has gained considerable momentum in recent years, to the point where ergonomists are playing less of a reactive role and migrating into the design process. One of the key criteria for proactive ergonomics is efficiency during the product development process. In order to stay competitive in the consumer market, manufacturers are driven to shorten the development time for a new product, thereby responding to trends more quickly, as well as reducing cost and increasing the total number of products introduced in a given time period (Feyen et al, 2000). This goal has been accomplished largely due to the use of computer-aided design tools. The same holds true in ergonomics, where computer generated environments and digital humans allow analyses to be performed without ever requiring physical data or prototypes. This trend towards computer-aided ergonomics has been observed in the military as well as a number of manufacturing industries including; the automotive, clothing and aviation sectors (Yee & Nebel, 1999; Rigel et al, 2003; Dai et al, 2003; Blome et a;, 2003; Doi & Haslegrave, 2003). A variety of human modeling tools have been introduced for the purpose of ergonomic analyses, such as RAMSIS, SafeWork, and Jack (Reed et al, 2003). These software programs allow users to create virtual environments and generate human models within those environments. Once this is done, the user can manipulate their human model to interact with the surroundings as they predict would be the case in a true physical environment. A variety of virtual analyses can be performed to predict the success of a product or workstation layout. Most software tools allow for clearance, posture, reach, line of sight and strength predictions (Blome et al, 2003). Thus, testing that would normally be performed in the physical world is now done without ever building a part or using a true human-being. In the automotive industry, this approach has been used frequently for occupant packaging to assess the drivers seated position, the view through the window, as well as driver and passenger access to various equipment and controls (Rigel et al, 2003; Dai et al, 2003; Reed et al, 2003).

Virtual reality has also been used to assess assembly line work within the automotive industry. For example, Dukic et al (2002) describe the process of using a digital human and computer generated vehicle to test a future car design at Volvo Cars Corporation. The authors suggest that approximately 1500 problems were identified and solved during the virtual verification. Some of the ergonomic problems addressed during this process included four scenarios where an operator could not horizontally reach the desired part, four instances of a part being too high to access, eight obstructions to an operators when assembling a part and five cases where the wrong tool was proposed for assembly. Despite the success of including virtual reality into the design process of a new vehicle, the authors caution that the success of this process can be severely affected by the user's knowledge and education, as well as communication between engineering teams.

In an effort to test the accuracy and usefulness of computer-aided ergonomic analyses, Ford Motor Company and the University of Michigan assessed an assembly task both virtually and using the physical environment (Feyen et al, 2000). The virtual environment was developed using AutoCAD to mimic the true layout for assembling a converter into the transmission housing located on a conveyor. AutoCAD was linked to a commonly used biomechanical software package, the Three-Dimensional Static Strength Posture Prediction Program (3DSSPP). Assembly of the converter to transmission task was analyzed for a 95th percentile male within 3DSSPP for both the virtual and physical environments. Four independent postures were assessed for peak low back compression, torso strength, hip strength and shoulder strength. Results for both the physical and virtual assessments show similar results for the low back; the NIOSH limit of 3400 N of peak compression was exceeded in each case. Both analyses led independent assessors to draw the same conclusion that biomechanical stresses for this task were high and a redesign was required (Feyen et al, 2000). These findings lend support to the use of virtual environments and digitally generated humans as a valid approach for ergonomic assessments during the design of a new part or workstation.

Despite the many advantages of utilizing digital humans in virtual reality to aid ergonomics, there are a number of factors to be considered that can affect the success of this approach. A common fault is to over-generalize the results of a virtual analysis by concluding that a job is 'good' or 'acceptable'. Ziolek & Nebel (2003) advise that virtual analyses will only assess those parameters that have been specified and that it is impossible for a software program to consider every possible factor. Perhaps one of the most important considerations is the difference between utilizing a digital human for an assessment and recruiting or observing a real human. While most software programs will, to some degree, limit the postures and range of motion obtained by a digital human, they do not account for the comfort of a given posture. Therefore, it is possible for the assessor to position a digital human in such a way that would never be chosen if a real human had been performing the task. This may lead to inaccurate results during the assessment of a job or activity if the postures analyzed do not reflect true human movement choices and strategies. Furthermore, digital humans do not account for all of the differences that may exist within a population. For example, an older, injured or disabled individual may perform very differently than a digitally generated human, which again would not be captured in a virtual simulation (Ziolek & Nebel, 2003). One method to overcome these limitations is the use of motion capture technologies. This allows a designer to capitalize on the benefits of a computer-generated environment, while also minimizing the errors which can result from employing a digital human during an ergonomic analysis. Furthermore, because the data collected from a real human in motion capture can be linked to a digital maniquin, the ability to analyze movement in an environment that does not yet exist has not been compromised.

MOTION CAPTURE TECHNOLOGY IN COMPUTER-AIDED ERGONOMICS

As computer aided ergonomics becomes a regular part of the design process for a new product, the drive to improve the accuracy and validity of this technology will increase. Some researchers and manufacturers have already been faced with this challenge and have sought ways to enhance their virtual reality laboratories. One of the major limitations of simply manipulating digital humans is the inability to accurately predict the motion path of a human being. Digital humans are capable of assuming both static and dynamic postures, with dynamics being the most difficult and time consuming to achieve. Predicting a motion path can be accomplished using a variety of software packages, but the user must manually program this. Motion paths are usually generated in one of two ways; by chaining together motion blocks, for example in walking, leg lifting can be programmed to occur repeatedly to create locomotion or alternatively, the user can indicate a start and end point and allow the software to predict the human's actions (Yee & Nebel, 1999). Both techniques can be tedious, especially when a series of complex actions must occur together. Motion capture technology is an alternative option for generating dynamic human motion within a virtual environment. This method alleviates the time consuming task of programming a motion series for a digital human and also ensures the movements will reflect true human actions.

A variety of collection devices have been used to track motion data. For example, ShapeTape™ (Measurand, Fredricton, New Brunswick, Canada) has fiber optic sensing arrays that track bending and twisting within the tape to capture movement. This can be placed on the limbs, torso and head to sense human movement (Danisch & Lowery-Simpson, 2003). Optical systems utilize infrared cameras to locate an object or human in space. Reflective markers are placed on the human and positional data are captured via camera and stored in a PC. Optical systems do not require a tether to a central processor, however this may occasionally result in lost data if the actions of the human block a camera's line of sight to a body marker (Yee & Nebel, 1999). This limitation can be avoided by ensuring the appropriate number of cameras is used. For example, when studying passengers entering and exiting a vehicle, Rigel et al (2003) found that quality motion data could not be obtained until the total number of cameras used in their study was increased to fourteen. This ensured that all 60 markers placed on the subject's body were sufficiently visible to the cameras during data collection.

Another common method of capturing motion is through electromagnetic devices which are used to track positional data in real time. The instrumentation required for this system is a central transmitter, which is connected to a central processing unit. This unit can have one or more sensors that are tracked in space based on its orientation to the electromagnetic field surrounding the transmitter (Maiteh, 2003). Agnew et al. (2003) used the Fastrak™ (Fastrak Systems Inc., Toronto, Ontario, Canada) magnetic tracking device to measure cumulative spine loading during sagittal plane lifting. This study introduced a method of reducing the time requirements associated with more traditional video-based procedures used to estimate cumulative loads. Cumulative compression was calculated by rectangular integration and results showed no significant differences between data collected from video and the magnetic Fastrak™ system with the average error across all conditions being only 2.2 % (Agnew et al, 2003). The Fastrak™ used in that study was only equipped with four sensors, thereby limiting the number of landmarks tracked on the body. Given this constraint, Agnew et al (2003) were restricted to movements in the sagittal plane and a single-equivalent muscle biomechanical model to estimate low back loads. Nevertheless, a method of acquiring and processing cumulative load data in real time was proposed and confirmed. While magnetic tracking devices allow data to be concurrently processed and ensure a true representation of the movement patterns of the subject, there are limits to its application. In most cases, electromagnetic tracking devices are limited to laboratory settings given that interference with metallic objects or power sources will distort data. The magnetic fields from ferrous metal objects distort the transmitter field of the motion capture system, which ultimately causes the positional data to drift, altering results (Agnew et al 2003; Jayaram & Repp, 2001; Yee & Nebel, 1999).

Using an Ascension (Ascension Technology Corporation, Burlington, Vermont, USA) electromagnetic motion capture system, integrated with the Jack human motion analysis software, Maiteh (2003) demonstrated how virtual ergonomic analyses can be performed in both proactive and reactive scenarios. When performed reactively, the author suggests that a video of the operation in question should be taken and a virtual environment built to replicate the true setting. An operator can interact with this environment in a motion capture lab in order to identify critical movements. These movements can then be analyzed using a software package such as Jack. If a job is assessed proactively, the analyzer can review the virtual environment that is being proposed and determine which variables require ergonomic consideration. A digital human can be programmed to follow the anticipated motion paths or more desirably a motion capture system can be used to generate true motions for analysis in a software program (Maiteh, 2003). Using a motion capture facility and Jack software the author reviewed several scenarios for an automotive sub-assembly task and advocate the use of motion capture as a more accurate and time efficient method for job analyses.

DEFINING HUMAN REACH AND ACCESS PARAMETERS USING MOTION CAPTURE TECHNOLOGY

Motion capture systems have frequently been used to study human reaches and accessibility in the automotive industry, however this has primarily been from an occupants (driver's) perspective. A common variable of interest in these studies are human reach zones like, for example, a reach to the radio dials on an instrument panel or a reach to the glove box from the drivers seat. Furthermore, ingress and egress (vehicle entry and exit) have also been frequently studied as this is generally the first encounter and impression a customer will have with the vehicle. BMW Automotive manufacturers recognized the rise in customer demands when purchasing a new vehicle and, thus, have dedicated more resources to the study of occupant safety and comfort (Rigel et al, 2003). Using the Vicon 624 motion capture system with the RAMSIS human simulation model, BMW assessed the various methods of vehicle entry used by customers. A Variable Ingress and Egress Mock-up (VEMO) was used to simulate the vehicle geometry of all BMW models and can be adjusted to size through both manual and electric controls. The Vicon infra-red cameras passively tracked positional data from 60 markers on the human body. This data was collected for 210 subjects and results showed three different types of ingress methods; 1) slip-in, where the right leg contacts the floor pan on left side of steering column first; 2) threader, where the right leg is positioned immediately on the right side of steering column and 3) plumper, where the driver's buttocks is first inside the vehicle and he/she 'falls' into the seat before bringing the legs into the car (Rigel et al, 2003). Through use of a motion capture and analysis laboratory, BMW was able to determine which methods of vehicle entry were used most frequently and by which customers. For example, it was found that entering with the buttocks first (plumper) was more common among those with a higher body weight. Overall, the motion patterns captured led the authors to conclude that the slip-in strategy was used by the majority of customers and future vehicle designs can account for this preference (Rigel et al, 2003).

The human body is capable of moving in an almost infinite number of ways, which is a challenge for computer-aided ergonomics. Even when given the same goal, subjects may utilize very different movement strategies based on their size, gender, age and physical comfort. The coordination of several body segments to execute a task can vary widely among different populations. This poses a problem when attempting to design a product that can suit the needs of multiple customers. It also touches on the limitation of utilizing digitally generated humans and pre-programmed motion patterns to assess a task or a product. One pre-determined reach strategy cannot be expected to account for the wide range of movements seen among various human populations (Chaffin, 2002). To date, one of the best methods available to accurately determine human motion paths is to use motion capture technology. This has been employed by the University of Michigan in several studies, each of which has contributed to the understanding of human motion and enhancement of digital human motion databases (Chaffin, 2002; Park, Chaffin, Rider, & Martin, 2003; Chaffin & Faraway, 2000). Recent research has not only shown that digital humans are not the best predictors of human movement, but also that true humans can utilize several different strategies to accomplish the same goal. As such, it is important not only to include true humans in ergonomic analyses, but also to accurately reflect the population of interest. Chaffin & Faraway (2000) studied the right-arm reach motions of a diverse group of participants using a vehicle mock-up consisting of the typical controls seen on an instrument panel, an adjustable driver's seat and driving scene displayed on a large monitor. A total of 38 reach targets were included in the vehicle mock-up and subjects were given audible cues when required to contact the target. The motion patterns of each subject were tracked using a four-camera MacReflex™ optoelectronic motion capture system (Qualisys. Gothenburg, Sweden) which resulted in a linkage of 18 joint angles to be analyzed for significant differences in reach patterns by age, stature and gender. Several inter-group differences were noted when subjects were asked to reach to the four main areas in the vehicle mock-up; console, radio, overhead and to the far right (Chaffin & Faraway, 2000). For example, less severe segment angles were found among people of larger stature and when stature was held constant, older individuals tended to keep their arms closer to the body when possible. The differences seen between men and women may be largely attributable to stature but also impacted by inherent differences in factors such as strength and shoulder breadth (Chaffin & Faraway, 2000). Information presented in this study suggests that the digital humans found in ergonomic software packages may need to account for more than just anthropometrics when assessing differences in movement strategies. Furthermore, research aimed at studying human reach capabilities cannot rely on a homogenous sample to accurately represent human motion as movement is dependant on a variety of factors.

III. METHODS

SUBJECTS

Approval for data collection was granted through the University of Windsor Research and Ethics Board. Twenty employees of Ford Motor Company participated in this study. All those recruited were Operators within the Vehicle Operations Pilot Plant (VOPP) located in Dearborn Michigan. The Pilot Plant is where the first physical prototype of each new vehicle model is assembled. This subject sample included females and males with five subjects in each of four anthropometric height ranges (5th female or 5F, 50th female or 50F, 50th male or 50M and 95th male or 95M) (Table 1). The anthropometric measures of this sample can be compared to the population values from the Jack Classic Human Simulation Software.

Table 1. The age, height and weight of each subject with group averages and standard deviations. "Pop Value" represents the values used in the Jack Software (ANSUR 1988, US Army Natick Soldier Center).

	Age (years)				Height (cm)				Mass (kg)			
	5F	50F	50M	95M	5F	50F	50M	95M	5F	50F	50M	95M
1	46	57	46	35	153	162	174	187	59.8	91.4	92.7	84.1
2	48	41	40	34	154	163	176	187	94.1	69.5	74.5	96.8
3	24	51	41	52	154	163	176	187	57.7	79.8	93.9	103.2
4	29	48	32	38	153	162	176	187	74.1	76.6	85.9	84.1
5	25	53	43	33	152	163	175	186	46.4	63.0	86.6	106.1
Mean	34.4	50.0	40.4	38.4	153.2	162.6	175.4	186.8	66.4	76.0	86.7	94.9
StDev	11.7	6.0	5.2	7.8	0.8	0.5	0.9	0.4	18.3	10.8	7.7	10.4
Pop Value					151.4	162.2	175.9	187.1	47.7	62.5	78.9	103.2

The study was conducted within a motion capture lab at the Work Center for Human Simulation (WCHS) which is located adjacent to the VOPP. The WCHS has an agreement with the Plant Manager to allow workers to report for duty to the WCHS if they consent to participate in the research study being conducted. Therefore, the researcher was able to provide a list of required participants and a description of the study to the VOPP Health and Safety Coordinator, who then recruited 20 injury free and willing participants.

STUDY VARIABLES

Dependant Measures

The variables that were measured in this study include: cumulative and peak low back compression at spinal level L4/L5 as well as peak and cumulative resultant shoulder moments for the left and right arms. Cumulative compression and moment were calculated by rectangular integration of the load time history for each task at a rate of 30 frames per second. Peak compression was defined as the highest compressive force seen at the L4/L5 joint. Peak moment was determined to be the highest resultant moment seen for both the left and right shoulder

In addition, at the point of peak compression, kinematic variables (measured in degrees) were recorded in order to evaluate the postures adopted by each subject. These included: spine flexion/extension, axial twist and lateral bend rotations, as well as shoulder abduction/adduction and elbow flexion angles.

Independent Measures

Three automotive assembly tasks were performed in sequence during one motion capture session. Data from the combination of all three tasks were used to assess cumulative loads. For determining peaks, the 3 tasks were individually parsed from the motion capture data. The three tasks that were simulated in the lab and evaluated were;

1) a reach across the front fender into the engine compartment to make a 2-handed hose insertion
2) reaching under the instrument panel to telescope the intermediate shaft, and

3) reaching to the centerline radio antenna to make a one-handed electrical connection.

There were four groups of subjects (5th female, 50th female, 50th male, 95th male). This represented the True Anthropometry (TA) independent variable. All subjects performed each task under 4 different conditions; once when they were represented in motion capture as their actual body size, and three additional times when they were scaled in motion capture to represent another set of anthropometric measures. This represented the Scaled Anthropometry (SA) independent variable. Subjects repeated each condition a total of 5 times and data from 3 trials were used in the final assessment. Selection of the three trails was based on the quality of the motion capture data, thus trials requiring the least amount of post-processing (due to poor or missing data) were chosen. If the quality of all five trials was acceptable, the first 3 were selected for post processing. The three independent variables, and their levels, can be seen in Figure 1 below.

STUDY TASKS

The tasks performed in this study represented simulations of real jobs seen within automotive assembly plants across the United States and in Canada. To study these tasks in a lab setting, a computer simulation software program was used to create a virtual environment where subjects, moving within a motion capture environment, were linked to a human manikin within the software and could simulate the tasks on a digital vehicle. The tasks were chosen to represent three different reaching scenarios which placed kinematic demands on the subject and could potentially be performed using a variety of movement strategies. The digital vehicle data for a 2005 Model Year Ford Focus was accessed from Ford's database (Process Driven Visualization, PDV) and imported to a software package known as Jack Classic Version 4.1 (UGS, Plano, Texas, USA) (Figure 2). This created a virtual environment where the movements of the subject captured in the lab were translated into a human model in Jack. This environment was projected onto the wall of the laboratory for the subject to view. As the subject moved through space, the human model acted as a mirror image and thus, by watching the projected picture, subjects could maneuver themselves around the vehicle. A number of physical props were used to provide tactile feedback to the subject in the lab. This will be described in more detail later in the Methods.

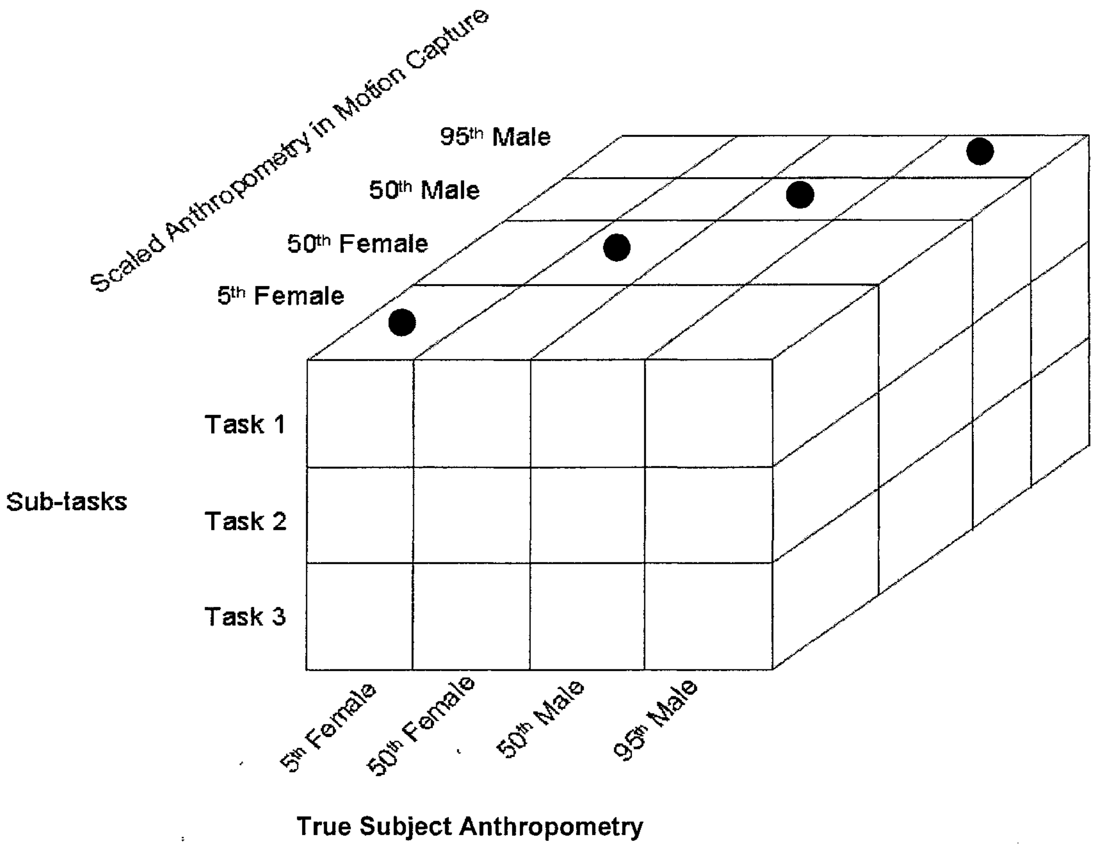


Figure 1. The variable matrix above represents the three independent variables and their various levels. The black dots indicate the conditions where subjects performed tasks scaled to real dimensions (ie, they were scaled to their true anthropometry)

The real vehicle dimensions provided below reflect those that were used during trials where subject were tested with their True Anthropometry (TA). When subjects were scaled in virtual reality to represent the other three sets of anthropometric measures, the physical environment was manipulated (ie scaled) to reflect that body size. For

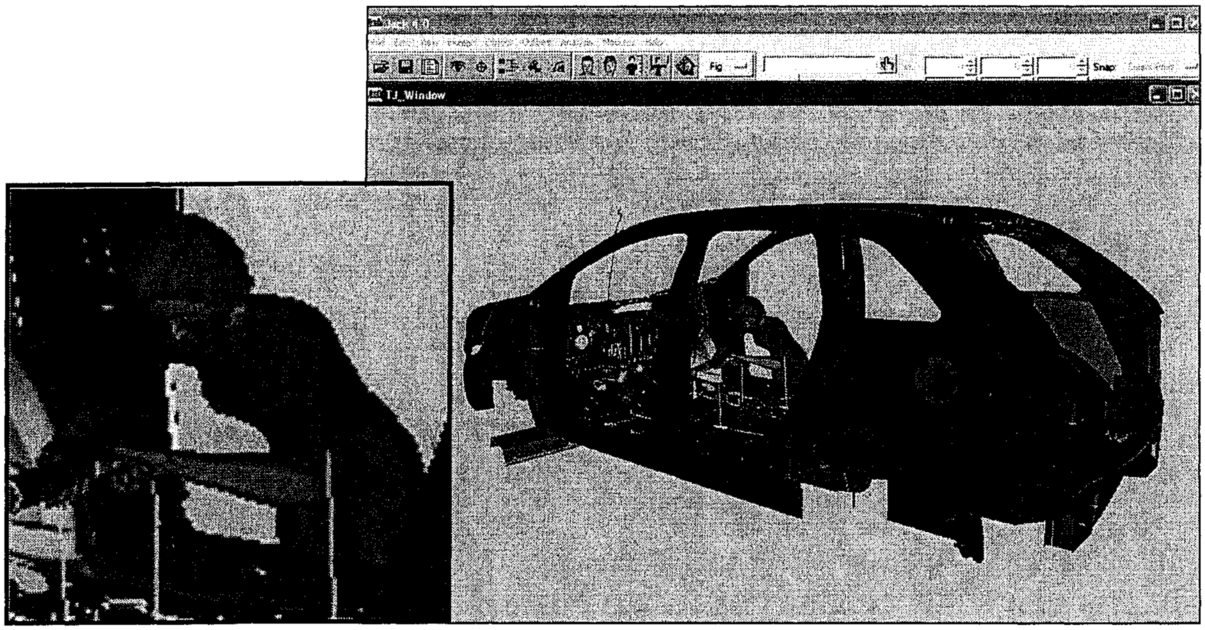


Figure 2. The interface of JACK software with the digital vehicle and tool renderings. This image depicts a 5th percentile female model securing a bolt in the center of the floor pan of the vehicle.

example, when a subject with a TA of a 95th percentile male was tested with a SA of a 5th percentile female, the dimensions of the virtual environment and vehicle were scaled such that objects were moved further way from the subject horizontally and the vertical height of physical props was increased (such as the front bumper or door sill). The physical environment was scaled based on the difference in height of the true and scaled anthropometry, for example if a 1.76 m person (TA = 95th male) was scaled to a 1.53 m person (SA = 5th female), all objects would have been scaled up in size by a factor of 1.15 (1.76/1.53). Specifically, if an object is located 0.60 m horizontally from the 95th percentile male subject in the unscaled environment, it would be moved 0.60 x 1.15 = 0.69 m horizontally from the subject when he was scaled to represent a 5th percentile female. In the virtual environment, the Jack human manikin was also scaled to appear as a 1.53 m tall female.

All tasks were performed in sequence to represent a true assembly process flow. While tasks were always performed in the same order, the order of presentation of the four scaled anthropometric conditions was randomized for each subject. The physical mock-up and task flow is described below.

Reaching to make a hose insertion in the engine compartment

For this task, when subject's were scaled to their actual anthropometry, they were required to stand at the front of the vehicle and reach 0.91 m horizontally into the engine compartment to install a hose with both hands, using a power grip around the hose (see Figure 3). Subjects were asked to push down on a 4 cm diameter rubber hose which was wrapped around wood doweling and fixed to a sheet of plywood. The hose was raised 1.02 m from the ground and placed 0.91 m horizontally from the subject's body. On a real assembly line, the operator is able to lean over the front bumper during this type of task, so a supporting surface was also provided in the lab. A plastic block (0.075 m tall, 0.60 m long and 0.20 m deep), with contoured edges, was placed on the table top near the edge so the operator was able to lean on this surface. When the environment was scaled to represent another anthropometric condition, the height of the table (including the height of the hose) was adjusted accordingly; however, the height of the block/leaning surface relative to the height of the table remained constant for all conditions. This decision was made because the block was only 7.5 cm in height, and the maximum adjustment that would have been made was 1.13cm, It was assumed that such a small adjustment would not affect the results. A vertical reach to the hose of 0.91 m was selected because this is the maximum forward reach of a 5th percentile female when supported at the pelvis (leaning) and using both hands to manipulate an object. This was determined using the Jack software. Given that tasks were to be performed by all subjects, it was imperative that the task demands did not exceed the capabilities of any subject group, and the 5th female is generally used as the limiting anthropometry for reaching activities.

When subjects had completed the hose insertion task, they were asked to stand upright and walk to the driver's side door on the side of the vehicle to perform the next task.

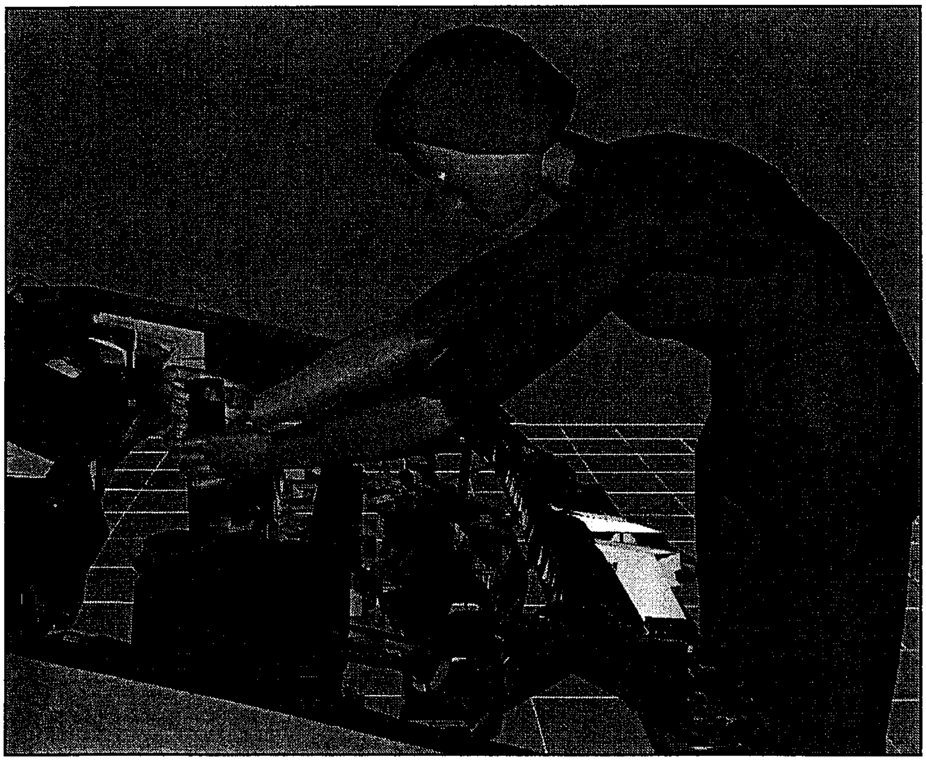


Figure 3. The manakin in this picture can be seen reaching across the front bumper to make a hose insertion in the engine compartment.

Reaching under the instrument panel to telescope the intermediate shaft

Once in front of the driver's side door opening, the subject was required to reach inside the vehicle to the left and locate the intermediate shaft which was found under the instrument panel (see Figure 4). The intermediate shaft connects the steering gear to the steering wheel. On an assembly line, the shaft is connected to the end of the steering wheel and must be pulled in a downward direction to connect it to the gear. The portion of the shaft which is accessible to the operator's hand is approximately 0.18 m in length and 0.025 m in diameter. Subjects were asked to simulate the secure of the shaft to the gear by grasping a metal pipe placed over wood doweling, with a one-handed power grip, and push downward. An adjustable table was used to represent the height of the vehicle floor pan and was placed at 0.84 m from the ground (unscaled environment). The horizontal reach to the intermediate shaft was 0.61 m which was measured from the left edge of the driver's side door opening to the centre of the shaft. A plastic door frame was used to represent a real door opening and was placed on top of the adjustable table with an aperture of 0.97 m high by 1.07 m wide. All dimensions represent the unscaled environment. For conditions where subjects were scaled to one of the three anthropometries different than their own, the dimensions were modified appropriately.

Subjects were not encouraged to perform the task in any particular way, however, one restriction was enforced; subjects were not permitted to climb onto the adjustable table, which would represent climbing onto the floor pan of the vehicle. This is a true restriction seen in the automotive assembly plants and thus was adhered to in this study. Once the subject had completed the action of securing the intermediate shaft, he/she was asked to stand upright and the task was considered complete.

When subjects had completed the intermediate shaft task, they were asked to walk away from the vehicle mock-up to a spot, identified by a tape marking on the ground, and stand upright and relaxed for 5 seconds. During this brief delay, the researcher intervened to place a 0.51 cm high platform in front of the driver's side door opening in preparation for the next task. Once the 5 second delay was complete, the subject was able to begin their third and final task.

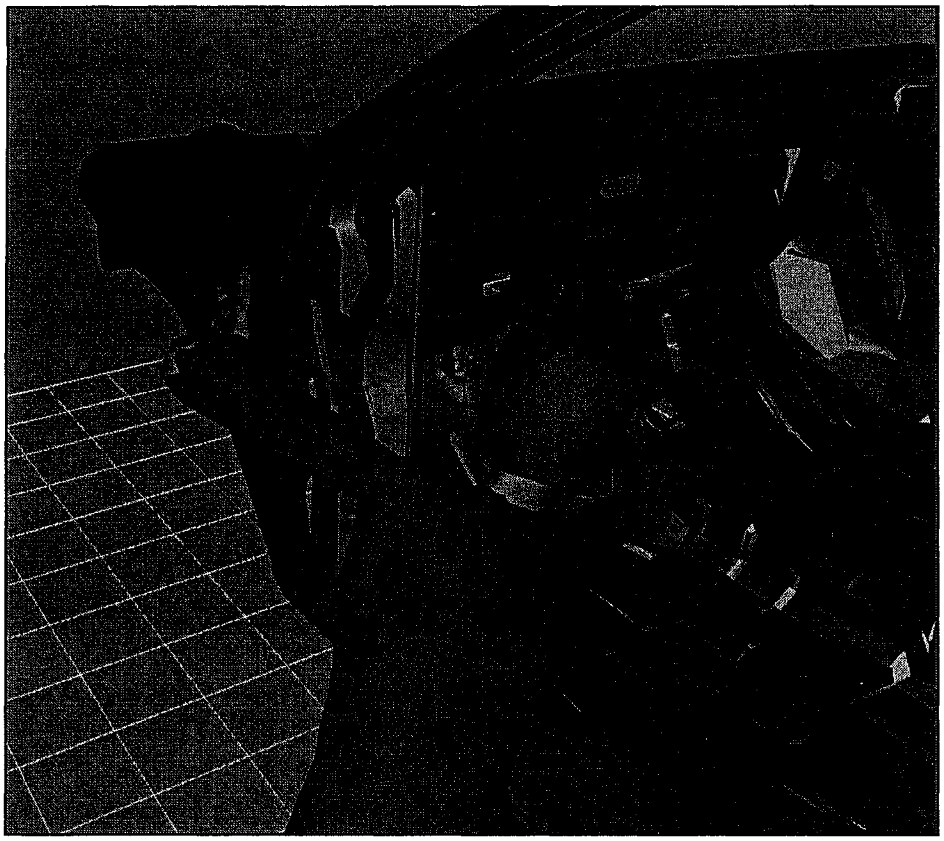


Figure 4. This picture shows a manikin leaning into the driver's side door opening of a vehicle to secure the intermediate shaft.

Making an electrical connection to the centerline antenna

To begin the final task, subjects were required to step up from ground level onto a platform that represented the true assembly line height for connecting a centerline antenna. Subjects were required to reach through a door opening (same prop as used for intermediate shaft connection) to the inside roof where the radio antenna prop was located. The horizontal location of the radio antenna was 0.53 m from the outside edge of the door frame and was represented by a household electrical light switch, oriented parallel with the ground. Using one hand, subjects were asked to simulate making an electrical connection, by pushing upward to flip the switch "on" (see Figure 5). The driver's side door opening followed the same dimensions as for the previous task (reaching to the intermediate shaft), however, in order to simulate the roof, a wooden frame was constructed and secured to the top edge of the door frame. The electrical connection prop (light switch) was fixed to the wood frame and located 1.58 cm above the platform surface when unscaled. When this task was complete, the subject was asked to step down from the platform and stand relaxed, this signaled the end of one full trial. This cycle of three tasks was repeated a total of 5 times for each of the scaled anthropometry conditions.

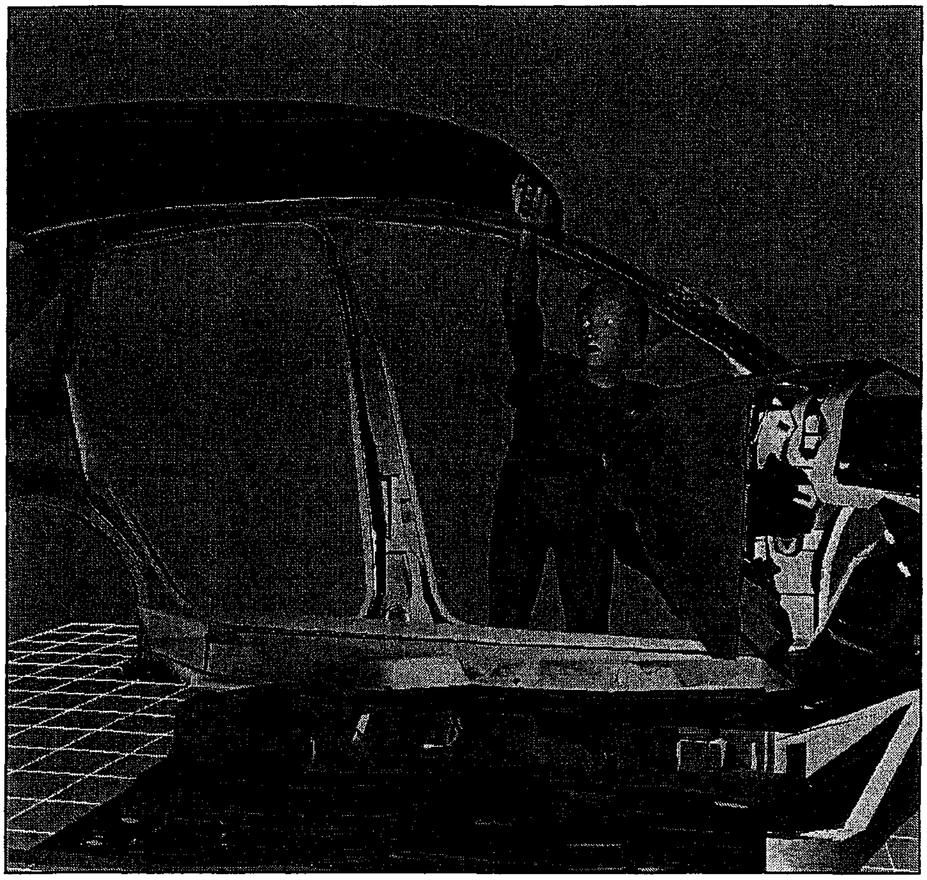


Figure 5. Virtual reality illustration of a digital human model making an electrical connection to the centerline antenna.

DATA COLLECTION

Motion Capture

A 10 camera passive optical motion capture system from MotionAnalysis (EvaRt 4.0, Santa Rosa, California, USA) was used to collect all motion data (see Figure 6). Cameras were mounted to an over head rail 3.0 m from ground level. A Dell Precision650 (Round Rock, Texas, USA) workstation with dual 2.4 Ghz Hyperthreaded Intel Xeon CPUs (Santa Clara, California, USA), 3.5 GB of RAM, 146.8 GB 4-disk SCSI RAID 0 Array hard drives, Nvidia Quadro FX 1000 Graphics card (Santa Clara, California, USA), and Windows XP Service pack 1 operating system (Microsoft, Redmond, Washington, USA) was used to store the data. Two 19 inch LCD monitors with 1280x1024x32 bit colour displayed data during collection and post processing. An LEC NT20 projector (Texas Instruments Technology) with XGA (1024 x 768) resolution was used to display the virtual environment on the wall during each trial. Data was collected at a rate of 100 frames per second (fps) as it was found during pilot testing that the system did not track as well at less than 100fps. The motion capture system/environment was calibrated daily using two methods, *square* and *wand* calibration. The square calibration used an L-shaped object that had a marker placed at the joint between the two sides, one marker placed on the shorter end of the L and two on the longer end. The joint of the L was placed at the origin (0, 0, 0) of the motion capture environment (centre of room) so the exact location of these markers was known. Secondly, the wand calibration was completed. A wand with precisely located markers was waved throughout the entire motion capture volume by someone wearing no reflective material or markers. The wand calibration was completed to ensure that all cameras had measured an object of known size throughout the entire environment. Using data from both the square and wand calibration methods, a maximum calibration error of 1.0 mm was considered to be acceptable. If this was not met initially, the calibration process was repeated until error measures of less than 1.0 mm were obtained.

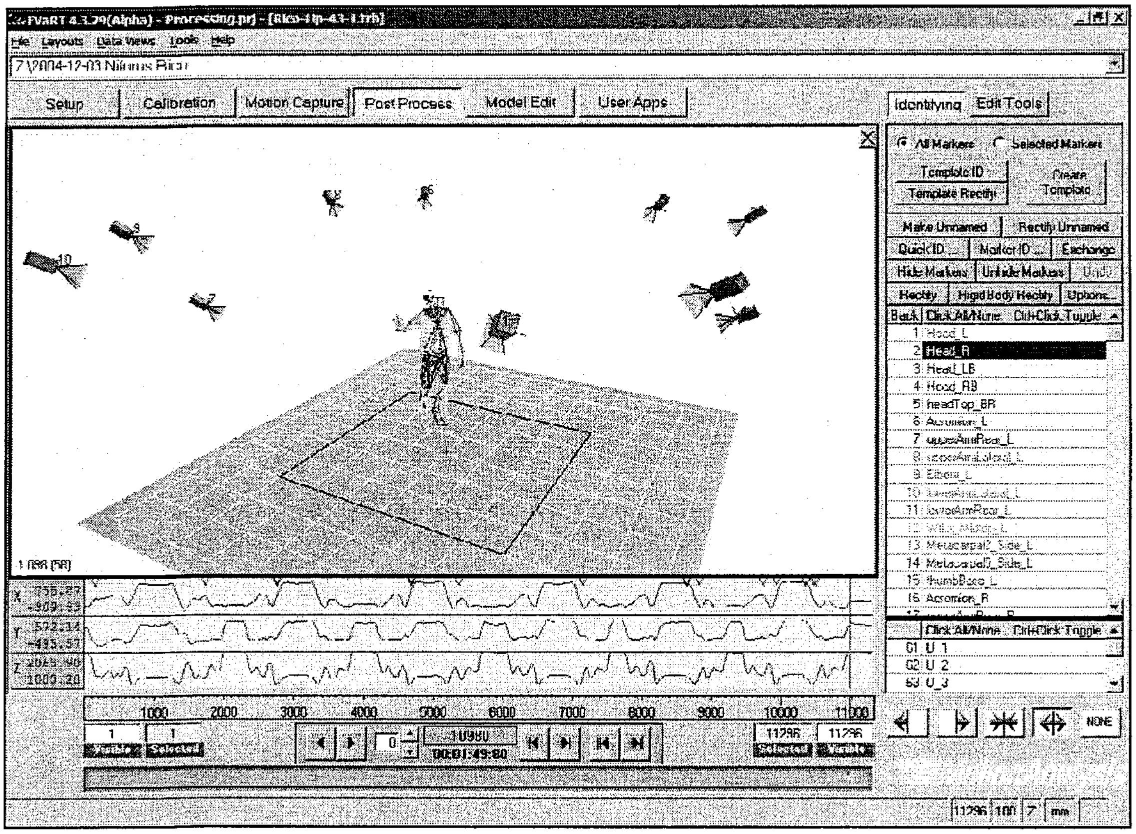


Figure 6. The user interface for MotionAnalysis, the motion capture software is shown.

The 38 markers were required for data transfer from MotionAnalysis to Jack Classic. Using the Motion Capture Toolkit within Jack, these markers are automatically registered and connected to the human figure. Each of the 38 markers seen in figure 7 represents a site where a constraint is drawn between the figure and a marker. These constraints are what drive segment motions of the human. Furthermore, there were certain 'rules' that needed to be followed for successful data transfer to occur. Positioning of the head, pelvis, and ankle on the Jack human mannequin depended on the markers being placed in the same horizontal plane as when the subject was in a standing posture. If the markers on these segments were not level in the standing posture, an offset in the orientation of these segments was seen in Jack. For example, if the two markers on the back of Jack's head were lower than the two front markers, Jack appeared to be looking up.

An additional 30 markers (total marker set = 68) were used for this study to ensure accurate motion tracking and reduce the amount of post-processing required (see Figure 8 for all markers). Each marker name is included in Appendix A. Makers were named according to where they were placed on the body. Markers with a 10 mm diameter were applied to smaller segments of the body, where placement was closer together, such as the hands or feet. Markers with a 20 mm diameter were used on larger segments such as the back and legs. Symmetry was avoided when positioning markers on the subjects because markers on a single segment oriented in an equilateral triangle, can easily be reversed within the MotionAnalysis system. The same holds true if the marker orientation is the same on both hands and the hands become close to one another. In such cases, the left hand may be recognized as the right and vise versa.

PARTICIPANT PROTOCOL AND PROCEDURES

Participants were asked to report to the WCHS once for a 2-hour period. Individuals were asked to dress in clothing that allowed free movement but was also not bulky or baggy, as this was important for accurate and consistent marker placement. Prior to collecting data, subjects were weighed, asked their age and measured for height, as well as asked to sign an informed consent sheet (Appendix B). Participants were then suited with the 68 markers which were placed over the clothing and secured using two-sided medical tape and elasticized material bands. Once the markers were secured, subjects were asked to move through a range of motion about the low back, shoulder, elbow, hip and knee joints to ensure proper tracking in MotionAnalysis. Once successful tracking had been confirmed, a template was created for that subject by drawing a relationship between the markers that created a stick figure. Next, subjects were given instructions on how to perform each sub-task and a minimum of 2 practice trials were performed prior to recording data to ensure the subject was comfortable with the activities. The practice trials were also used to confirm that the markers were secure on the body and could be accurately tracked throughout the tasks. While the subjects were performing each task, they were able to view their actions in a virtual environment,

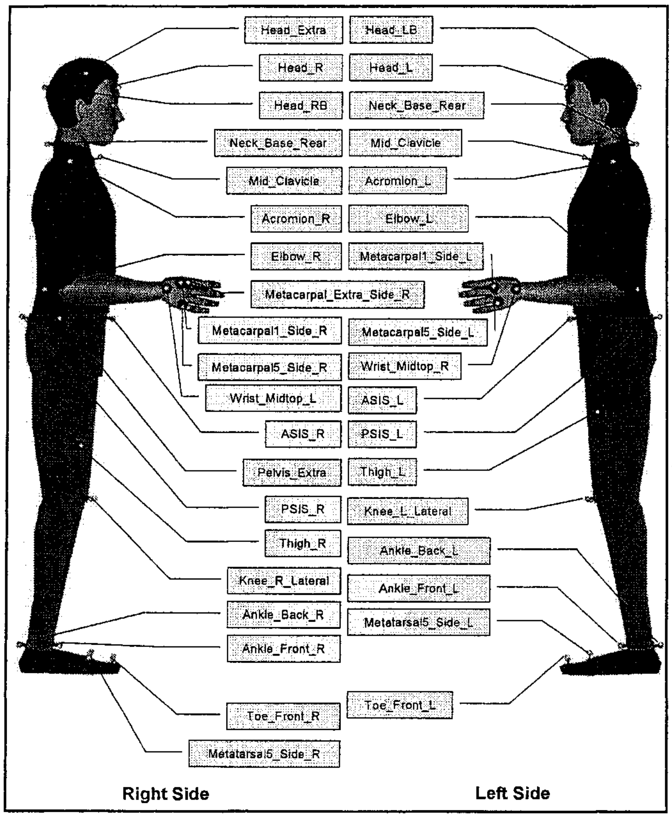


Figure 7. The marker placement required for data transfer into Jack Classic are shown above.

through an image projected onto the wall of the laboratory. This image reflected a virtually generated 3-dimensional vehicle and the human mannequin which was mimicking the motions of the subject in real time. All tasks were set up to be performed so the wall mounted image was project directly in front of subject. Thus, subjects could comfortably view the screen at all times and did not have to alter their posture in order to see the screen. To begin data collection, subjects were asked to stand upright with their shoulders flexed 90 degrees and held out to their sides, this allowed the researcher to briefly view the computer display screen hosting the MotionAnalysis interface and confirm that all markers were identified by the cameras. From this posture, subjects were

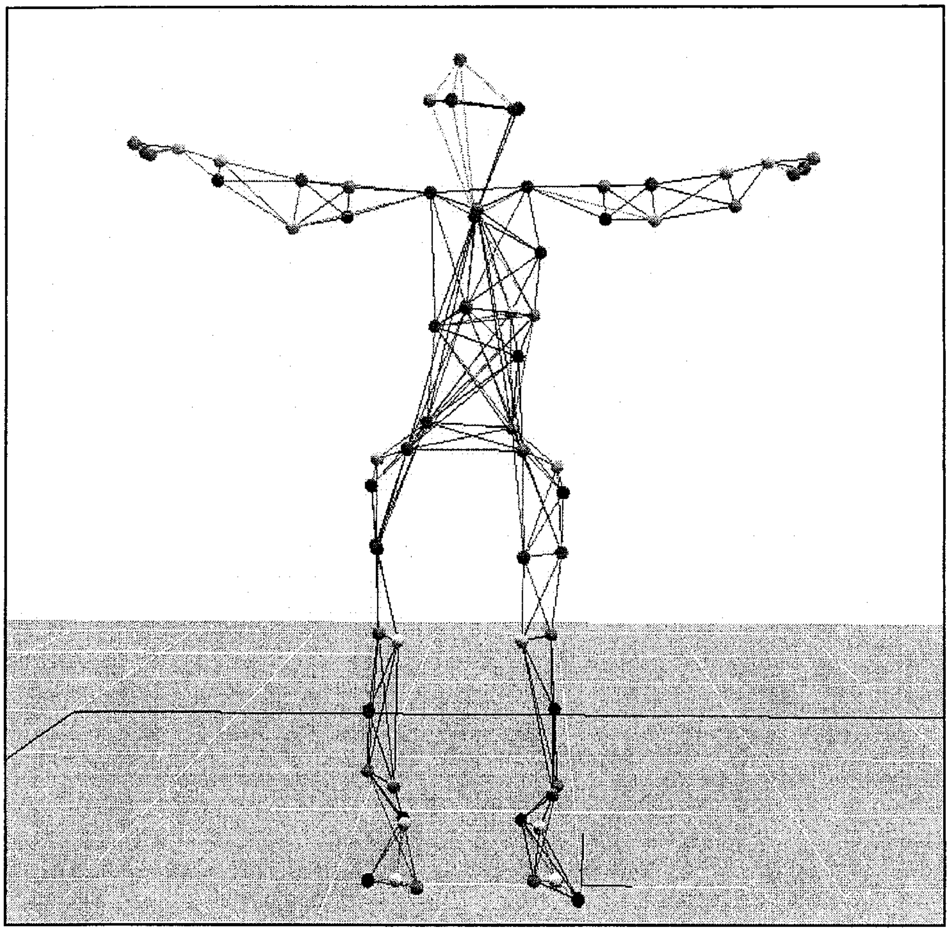


Figure 8. The full marker set used for motion tracking can be seen above. Each circle shows the location of one marker.

given a verbal cue to initiate the trial. After each trial was complete, subjects were asked to return to the starting position, while the researcher briefly checked the markers to ensure tracking had been maintained before the next trial began. This cycle was continued until all 5 trials were complete for each anthropometric condition. The order in which anthropometric conditions were performed was randomized while the order of the tasks remained the same across all conditions (hose, followed by intermediate shaft, then electrical connection). Between conditions, the subject was given a few moments of rest and during this time, the researcher prepared the lab and the virtual environment for the next anthropometric condition. Props were scaled accordingly and the size of the virtual mannequin was changed. When all 20 trials had been collected, the markers were removed and subjects were asked to return to their regular duties in the VOPP.

DATA ANALYSIS

Post Processing of Motion Capture Data

Once the motion data was collected, the raw 2-dimensional image data from each camera were saved (.vc format). Data in this format can be re-processed at any time if required. 'Tracks' files were also created (.trb format). This file contained the 3-dimensional motion data generated by the markers, and is the file format used during post-processing. Lastly, project files (.prj format) were created and contain all calibration information, camera orientation, frame rate, and the template for each subject.

Before transferring data to Jack, the project file and tracks file were opened together in MotionAnalysis for post processing. The tracks file is dependant on the data stored within the project file as it matches the motion data with the appropriate subject template and calibration information. Data was smoothed using a dual low-pass 4th order

Butterworth filter with a cut-off frequency of 6 Hz, which is consistent with recent literature using motion capture to assess low back loads during lifting as well as cleaning activities (Agnew et al., 2003, Azar et al., 2003; Lauder et al., 2003). Lastly, the data was played back in MotionAnalysis to identify any missing marker information. There are two types of corrections that can be made to address lost marker information. When the marker is visible, but not linked to surrounding markers (this is referred to as 'unnamed'), its relationship to the marker set is lost, but the data itself still exists. If this is the case, the unnamed marker can be manually re-linked to the main marker set at the first frame in which it is lost. Once the marker is renamed, the motion data is processed again and the gaps are filled in. The second option for post processing is used when marker data is truly lost or no longer visible. This occurs when a marker can not be seen by at least three of the 10 cameras during data collection and thus does not exist in the main marker set for a period of time. If this occurs, data must be replaced by creating a relationship to the missing marker and three additional markers (referred to as joining markers virtually). A virtual motion path is created for the missing marker by orienting it to the motion paths of surrounding markers.

In this study, 5 trials were collected and only three were used for data analysis. Each trial was reviewed for the quality of the motion tracking data, and 3 trials were selected based on which files had the least amount of missing data. Each trial was then post-processed according to the methods outlined above for correcting missing marker information. When all data had been smoothed and corrected, a new tracks file was created and this data was imported into Jack Classic.

Data Transition into the Jack Classic Software

Using the marker names specified in MotionAnalysis, the Jack software creates constraints between the marker location and joint segments on a human mannequin, which means that each marker is now locked to a location on the mannequin. The motion data for each trial was linked to a human mannequin and played in the Jack Classic Animation module to create a channel set (.env format). A channel set is a record of what is seen within the Jack environment, and thus creates a movie or animation of the virtual human moving through the motions path captured in MotionAnalysis. At this stage, the data is automatically decimated to 30 fps, which is the maximum frame rate in Jack. Once an animation of the trial had been generated, it was reviewed to identify each point when a subject had a load in the hand(s). This included the load associated with performing a task (for example, pushing downward to mimic a hose insertion) as well as any leaning forces assumed by the subject during a trial. For example, if the subject used the left hand to lean across the lift table towards the hose mock-up, this support load was accounted for. All hand load information was tracked using an excel spreadsheet which was converted to a text file and loaded into the Task Analysis Toolkit module in Jack Classic. See section entitled "Estimated Hand Forces" for more information on assumed hand forces.

The Task Analysis Toolkit (TAT) module in Jack Classic is a set of ergonomics analysis tools, including 'The Low Back Spinal Force Analysis' tool which evaluates spinal forces acting at the L4/L5 joint and the 'Static Strength Prediction' tool. This tool uses a link segment model developed at the University of Michigan to evaluate the percentage of a population that is capable of performing a task, based on the strength demands of the task and the capacity of the person being assessed (University of Michigan, Ann Arbor, Michigan, USA). Several other tools are included in the TAT, however, for the purpose of this study, only the two mentioned above were used. Using the animation module in Jack Classic, and a feature known as the TAT Reporter, the animation (series of movements performed by each subject), along with the hand load information, were processed through the TAT Reporter to generate a series of outputs from both the Low Back Spinal Force Analysis and Static Strength tools. The outputs provided information on a frame by frame basis (30 fps) for the following variables; low back (L4/L5) compression (peak and cumulative), shoulder moments about 3 axes (humeral rotation, adduction/abduction and anterior/posterior rotation) and joint angles of the elbow, shoulder, and low back at the point of peak compression.

Estimated Hand Forces

The following hand loads were used to represent each task within the study; For mimicking a two handed hose insertion, 43 N was placed in each hand (upward direction) for a duration of 0.5 seconds. A 60 N (upward direction) load applied for 1 second, was used to represent the task of installing the intermediate shaft (1-handed operation). These values were determined using the posture assumed during each task and assessing the strength capabilities for a 95th percentile female. The hand load that was considered acceptable to 75% of the population was chosen to represent each task. This criterion was based on the Ford protocol for safe job design. The hand load used for mimicking the electrical connection at the centerline antenna was based on the Ford specifications for designing safe installation of electrical connectors. This hand load was deemed to be 50.4 N (downward direction) and it was applied across 0.25 seconds.

Supporting hand forces were not collected originally. Given that subjects were not restricted in how they choose to perform the task, it was unknown apriori where individuals would choose to rest their hands. Therefore, it would not have been possible to position force plates within the vehicle mock up. Furthermore, if sites on the mock-up had been pre-selected for positioning force plates, subjects would have been biased towards leaning their hands at these specific sites, which may have impacted the results of the study. However, in order to provide an estimate of the leaning forces, a secondary study was conducted in the Occupational Biomechanics and Ergonomics Lab at the University of Windsor. This sub-study was conducted immediately following initial data collection in the Ford WCHS Lab.

The study was designed to determine the average leaning forces, as a percentage of body weight for each of the 4 anthropometric groups that participated in the main study (5th female, 50th female, 50th male, 95th male). Six male (height = 1.8± 0.05, mass = 88.7±6.8 kg) and six females (height = 1.6±0.04, mass = 60.4±17.3 kg) participated and all were faculty, students or staff at the University of Windsor. Each subject performed the tasks as a 5th percentile female and again as a 95th percentile male.

The original data collection were reviewed to determine all sites where subjects choose to place a supporting hand. These locations served as the four conditions to be tested in the sub-study, including; 1) leaning on the lift table while bending towards the hose, 2) leaning on the lift table while bending inside the door frame to access the intermediate shaft, 3) leaning on the side of the door frame when reaching towards the antenna electrical connector and 4) leaning on the top edge of the door frame when reaching towards the antenna electrical connector. Two locations were tested for the electrical connector task because subjects were observed using two different leaning locations during the initial data collection, therefore it was necessary to provide an estimate for both. A vehicle mock-up was designed to replicate the set-up described previously for primary data collection. The only difference in this study was that a virtual environment was not used. The physical environment was scaled to mimic the reach of a 5th female or 95th male and subjects were asked to reach for the physical props. Hand force data were collected using a 2.2 KN tri-axial load cell (XYZ Sensor, Sensor Development Inc, Lake Orion, MI, U.S.A.). Force signals were A/D converted using a 12 bit analog to digital multifunction I/O board (National Instruments) that was attached to a PC-compatible computer. The signals were sampled at 1024 Hz and digitally filtered using a Butterworth filter with a cutoff of 2 Hz. Forces in all three dimensions were measured, however, only forces in the direction perpendicular to the plate surface (Z) were presented as the X and Y forces were observed to be negligible.

The results for each of the 4 leaning scenarios are presented in Table 2 This data was computed as a percentage of body weight and a Repeated Measures Analysis of Variance (ANOVA) ($p<0.05$) with a 4 x 2 x 2 factorial design was conducted to determine if significant differences existed within the data.

Table 2. Data for each of the 4 leaning scenarios have been averaged across TA and SA. Data are presented as a percentage (%) of body weight.

		Males as 95th Male	Males as 5th Female	Females as 95th Male	Females as 5th Female	Group Average
Lean Across Engine Compartment	Mean	14.8	10.0	12.6	10.9	12.1
	St. Dev.	5.9	4.6	9.5	7.1	6.8
Lean on Floor Pan	Mean	7.1	5.5	11.0	7.5	7.8
	St. Dev.	4.4	3.0	6.0	4.4	4.5
Lean on Side of Door Frame	Mean	5.7	6.3	4.5	5.6	5.5
	St. Dev.	1.5	1.6	3.7	2.8	2.4
Lean on Top edge of Door Frame	Mean	7.4	8.0	6.8	9.8	8.0
	St. Dev.	2.4	1.9	3.8	2.2	2.6

There were no significant differences noted in the magnitude of the hand support forces, as a percentage of body weight, for any of the SA or TA conditions. Therefore, the following hand support forces, as a percentage of body weight, were applied in the main study for all anthropometric conditions; 1) 12.1% for leaning to reach the hose, 2) 7.8% for leaning when reaching for the intermediate shaft, 3) 5.5% when leaning on the side of the door frame 4) 8.0% when leaning on the top edge of the door frame for the electrical connection. Supporting hand loads during the electrical connection task were input based on whether the subject was seen placing their hand on the side of the door frame or on the top edge.

Determining Peak and Cumulative Loads

All reports generated using the ‘Low Back Spinal Force Analysis’ tool and the ‘Static Strength Prediction’ tool were further processed through a custom LabView program which was designed to extract the relevant data for this study. The peak compressive low back force was identified by finding the largest value within the data for each of the 3 tasks, individually (Figure 9). Furthermore, the corresponding joint angles at the point of peak compression were also extracted.

Cumulative compressive low back loads at L4/L5 were determined by integrating the area under the force-time history curve across all three tasks. When assessing cumulative loading, one trial is referred to as the sum of all the three tasks combined. The duration of an activity is an integral part of assessing cumulative loads, as this metric is an integration of the load-time history. Therefore, all trials were assessed across a common time period, 30 seconds, as this was determined to be the maximum time it took for any subject to complete one full trial. For any trial less than 30 s, an extrapolation technique was used to ensure all trials could be compared using a common duration. Extrapolations were completed by determining the difference between the actual task duration and 30 s. The difference in time was considered to be a period of rest, similar to finishing a job on the assembly line before the entire cycle time has elapsed. If a worker completes their duties before the next vehicle reaches their workstation, he/she is able to stand and relax. The period of 'rest' was multiplied by a resting low back compression value, which was based on a neutral standing posture with no load in the hands. These values were computed for each of the 4 anthropometric groups using the Jack Classic Low Back Analysis Tool (5th female = 275 N, 50th female = 340 N, 50th male = 430 N and 95th male = 550 N). The cumulative load calculated for the rest period was added to the cumulative loading incurred during the trial, and this summed value was deemed to be the total cumulative compression across a 30 second trial (Figure 9). The cumulative loading incurred during the trials was calculated as the sum of each force multiplied by 0.0333 s (1/30th of a second) across the duration of the trial.

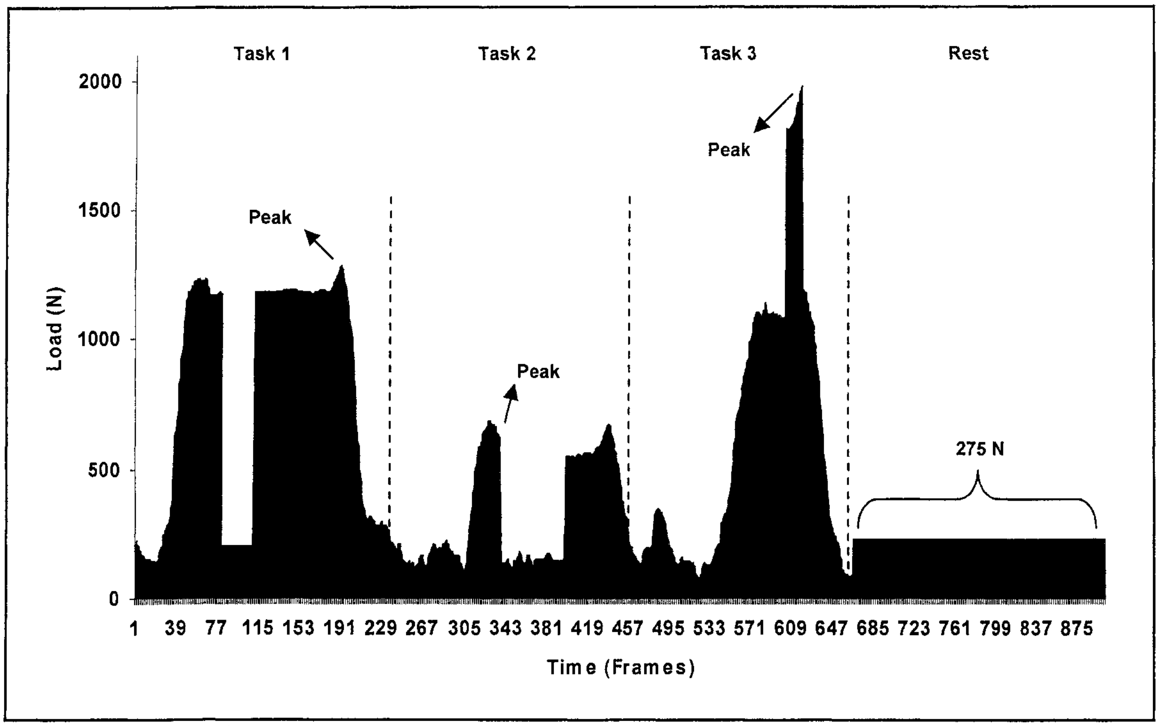


Figure 9. The load-time history for one trial has been presented. The point of peak compression for each task has been identified. The first 679 frames of data (22 sec.) represent the load from the 3 tasks. The data from frame 671 to 900 (22 to 30 sec) represents the period of 'rest' where the compression force of a 5F in a neutral standing posture has been added to the task time. The entire load-time history shown above represents the sum of the cumulative loading for one trial.

Peak and cumulative shoulder moments were also computed. Moments for humeral rotation (z'), forward/backward rotation (x') and adduction/abduction (y') were collected and a resultant moment was calculated from the three moments. The peak resultant moment for each trial was identified by finding the largest value within the data. Cumulative resultant shoulder moments were calculated using the same procedure as for cumulative low back compression. When extrapolating this data to reflect a time period of 30 seconds, the moment that would have accumulated during 'rest' was assumed to be zero because, in a neutral standing posture with the arms hanging freely at the sides, the moment about the shoulder is equal to zero.

STATISTICAL ANALYSIS

Data from the three repeated trials, performed for each condition, were averaged to represent the data for each subject. These values were then entered into the statistical analysis.

Individual statistical analyses were conducted for all dependant variables;1) cumulative low back compressive forces (N*s), 2) peak compressive force (N) at the low back and each of the following joint angles (degrees) measured at the point of peak compression; 1) spine flexion/extension, 2) axial twist and 3) lateral bend rotations, 4) shoulder abduction/adduction and 6) elbow flexion. Also included were; 7) left and right peak resultant shoulder moments and 8) left and right cumulative resultant shoulder moments.

The three independent variables were: 1) true anthropometrics (TA, 5F, 50F, 50M and 95M), 2) scaled anthropometrics (SA, 5F, 50F, 50M and 95M) and 3) task. (n=3). A 4 x 4 x 3 mixed analysis of variance (ANOVA) with repeated measures was conducted to test the null hypothesis that there are no significant main or interaction effects of the following independent variables; peak low back compression, peak resultant shoulder moment, trunk flexion/extension, lateral bend and axial twist angles, as well as left and right elbow flexion/extension and right and left shoulder adduction/abduction angle. The scaled anthropometrics and task were within variables (repeated measures) and the true anthropometrics was a between variable. It is important to note that, because data from all three tasks were combined and assessed as a complete 30 second process for cumulative low back loads and shoulder moment, a 4 x 4 factorial design was used to determine the effects of true and scaled anthropometrics on cumulative loading. If statistically significant effects were observed among any of the data, a Tukey's significant difference test was completed to explain where the variance occurred. All significance was evaluated at $p<0.05$.

IV. RESULTS

The results of this study are divided into three main sections. The data collected for cumulative low back compression are presented first. This is followed by the results for peak low back compressive forces and the associated segment angles observed at the point of peak compression. The third section focuses on the peak and cumulative resultant shoulder moments which were not a main focus of the study, but are reported and will be discussed from an exploratory point of view. These data were processed and analyzed identically to low back peak and compressive forces.

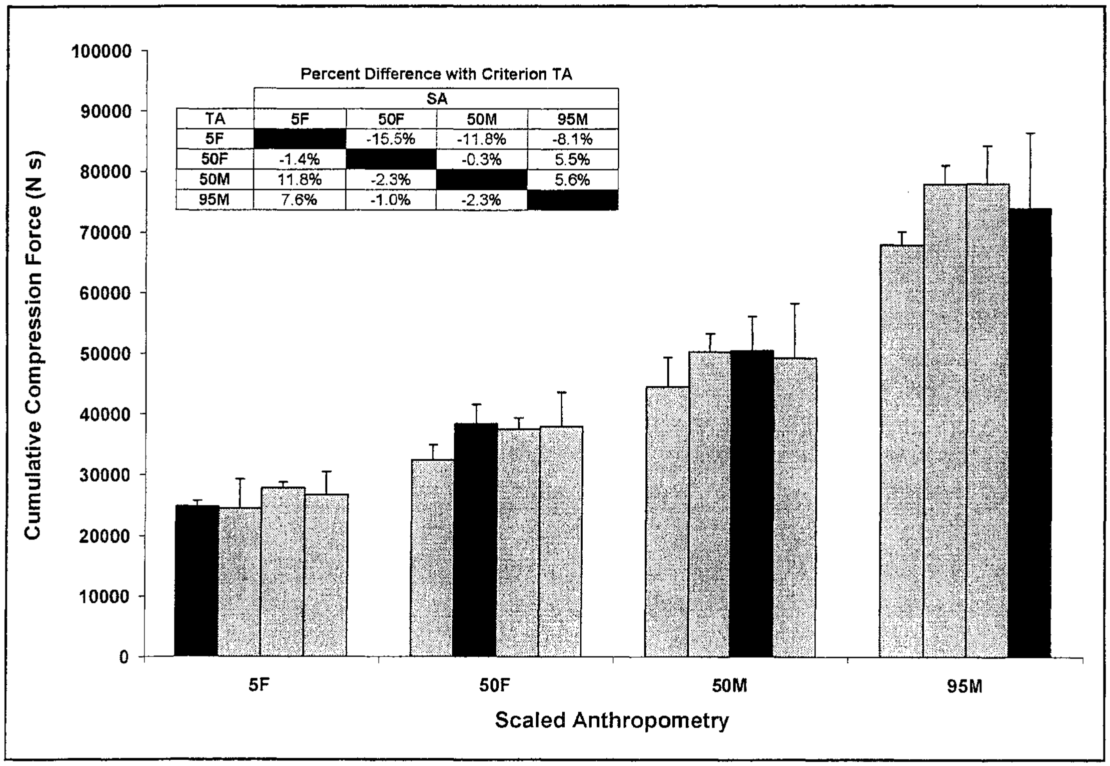
Statistically significant differences found for each independent variable have been summarized in Table 3. Post hoc analyses were completed in each case where significance was found.

PEAK AND CUMULATIVE LOW BACK COMPRESSION FORCES AT THE L4/L5 SPINAL LEVEL

There were no significant effects of TA for peak or cumulative low back compression, however, it is important to note that the 5F group tended to be different than the other groups (Figure 10 and 11). When the true 5F values are compared to that of the other three true anthropometries, the peak and cumulative compressive forces tended to always be lowest and this effect appeared to become more pronounced as scaled anthropometry increased from 5F to 95M.

Table 3. Summary of the statistically significant main and interaction effects of each independent variable based on the results of Repeated Measures ANOVA tests ($p \leq 0.05$).

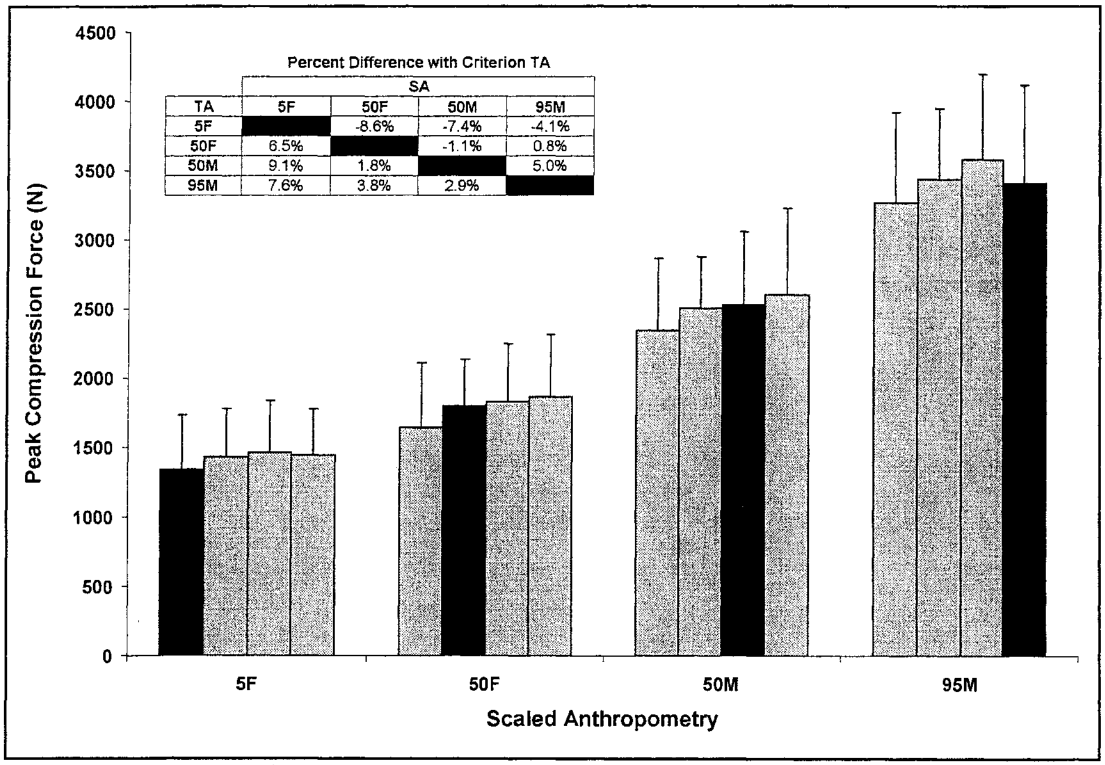
VARIABLE	True	Scaled	Task	True x Scaled	True x Task	Scaled x Task	True x Scaled x Task
Right Cumulative Shoulder		<0.0001	▨		▨	▨	▨
Left Cumulative Shoulder	<0.01	<0.0001	▨		▨	▨	▨
Right Peak Shoulder			<0.05			<0.05	
Left Peak Shoulder	<0.01						
Cumulative Low Back Loads		<0.0001	▨		▨	▨	▨
Peak Low Back Loads		<0.0001	<0.0001				
Trunk Flex/Ext Angle	<0.05	<0.0001	<0.0001			<0.0001	
Trunk Lateral Bend Angle		<0.001	<0.0001			<0.001	
Trunk Axial Twist Angle							
Right Elbow Flex/Ext Angle	<0.001		<0.0001		<0.01		
Left Elbow Flex/Ext Angle	<0.0001	<0.05	<0.0001	<0.05		<0.0001	
Right Shoulder Ab/Ad Angle			<0.001				<0.001
Left Shoulder Ab/Ad Angle	<0.05		<0.0001				



Percent Difference with Criterion TA

	SA			
TA	5F	50F	50M	95M
5F	■	-15.5%	-11.8%	-8.1%
50F	-1.4%	■	-0.3%	5.5%
50M	11.8%	-2.3%	■	5.6%
95M	7.6%	-1.0%	-2.3%	■

Figure 10. The average cumulative low back compression forces for each of the four SA scenarios. The black bars represent the criterion TA group (unscaled) group and the grey bars show each of the other TA groups scaled to represent the criterion. The order of adjacent bars in each cluster are, from left to right; TA=5F, TA=50F, TA=50M, TA=95M.



Percent Difference with Criterion TA

	SA			
TA	5F	50F	50M	95M
5F	■	-8.6%	-7.4%	-4.1%
50F	6.5%	■	-1.1%	0.8%
50M	9.1%	1.8%	■	5.0%
95M	7.6%	3.8%	2.9%	■

Figure 11. The average peak low back compression forces for each of the four SA scenarios. The black bars represent the criterion TA group (unscaled) group and the grey bars show each of the other TA groups scaled to represent the criterion. The order of adjacent bars in each cluster are, from left to right; TA=5F, TA=50F, TA=50M, TA=95M.

A main effect of SA was also observed for cumulative low back compression. This was a fairly linear effect, where differences were greatest between 5F and 95M (Figure 12). The progressive increase in cumulative load was 41% (from 5F to 50F), 33% (50F to 50M) and 53% (from 50M to 95M). Individual subject averages for cumulative low back loading can be found in Appendix C.

A main effect of SA was also observed for peak low back compressive forces, where magnitudes increased in a linear fashion from the 5F to the 95M (Figure 13). Significant differences were observed between all four SA conditions, where the lowest compression value was seen for the 5th percentile female group and increased in a step-wise fashion up to the 95M group. Individual subject data are presented in Appendix D.

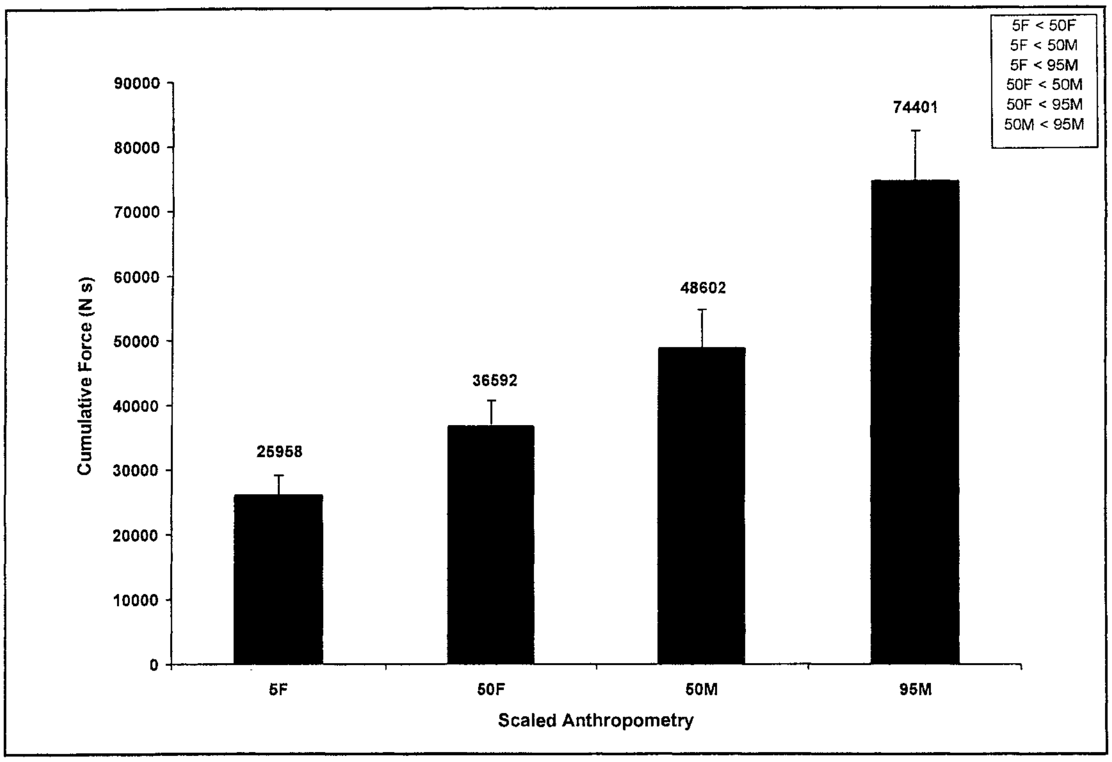


Figure 12. The main effect of SA for cumulative low back compression ($p<0.0001$). ($n=20$). Standard deviation bars are shown.

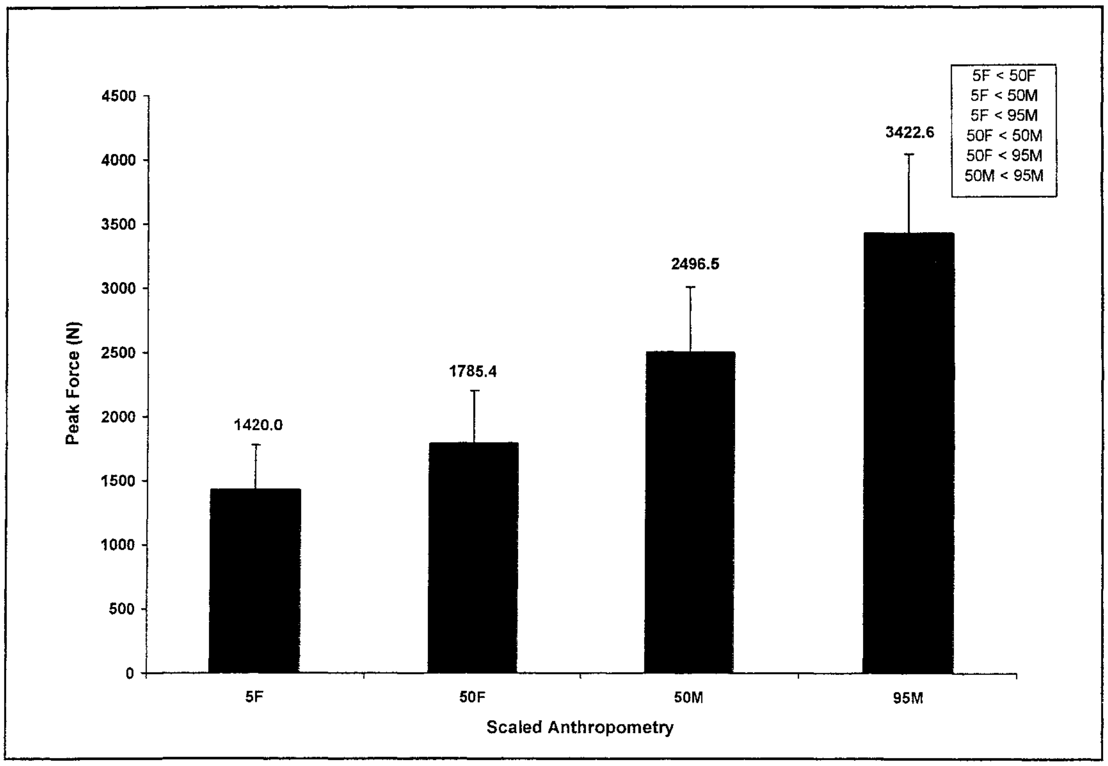


Figure 13. Main effect ($p<0.0001$) of SA for peak low back compression force. ($n=60$). Standard deviation bars are shown.

A main effect of Task was found for peak low back compression force (Figure 14). All tasks were found to be significantly different from each other, with Task 2 (intermediate shaft install) demonstrating the lowest compressive force demands on the back (magnitude = 1875N) and Task 3 (electrical connection to centerline antenna) producing the largest (magnitude = 2711N). The average of the peak compression values for all 3 tasks fell below the NIOSH Action Limit (AL=3400N). However, it can be seen that some individual subjects exceeded the AL (See Appendix D). This was only true for the two heaviest scaled groups (SA = 50M and 95M) and was most common for SA = 95M during Task 3.

KINEMATICS: JOINT ANGLES AT THE POINT OF PEAK COMPRESSION

Trunk Postures

A main effect of TA was found for trunk flexion/extension angle at peak compression force ($p<0.05$). Differences between groups only became significant as the gap in anthropometry increased. Significant differences were seen between TA=5F (7.3°) and both TA=50M (23.4°) and TA=95M (24.7°).

Figure 15 shows the significant interaction effects between SA and Task for trunk flexion/extension angle. In general, significant differences only existed when the difference in anthropometry became more extreme. The SA=95M trunk flexion angle was 23%, 92% and 35% greater than for the SA=5F, for Tasks 1, 2 and 3, respectively. No differences were noted between the 2 female groups (5F and 50F) or between the 2 male groups (50M and 95M).

Interaction effects of SA and Task were found for trunk lateral bend angle at the point of peak compression. Significant differences were only present for Task 3 (Figure 16).

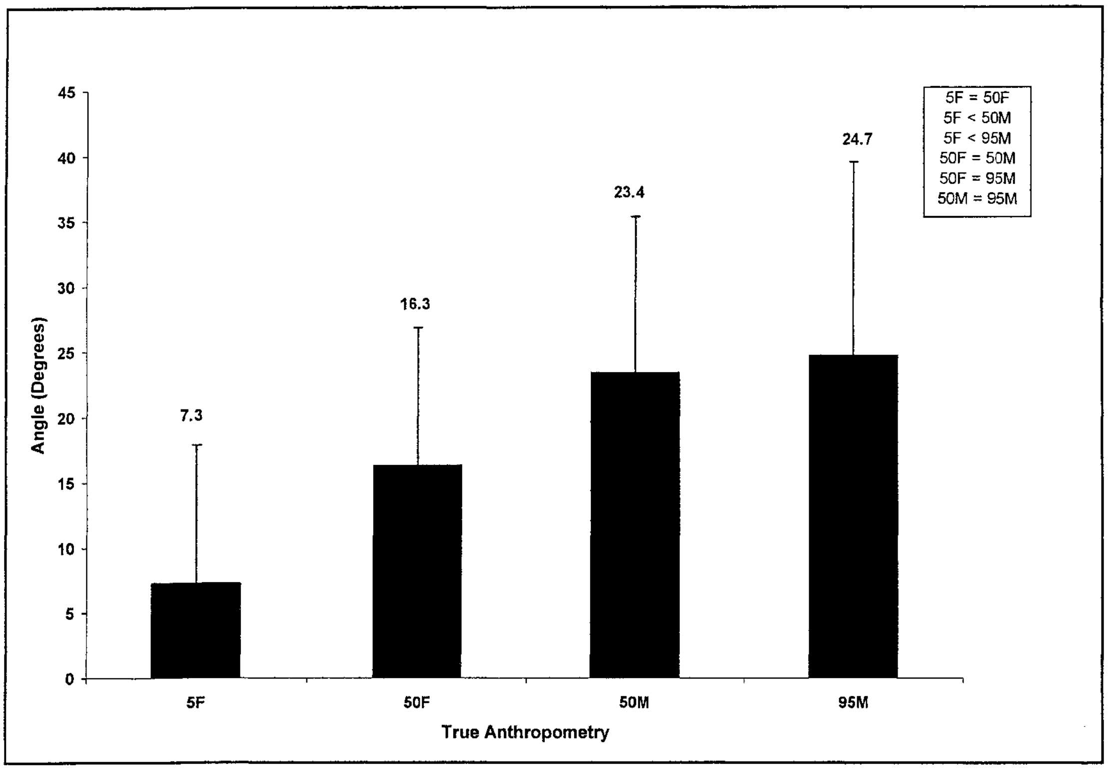


Figure 14. Main effect of TA for trunk flexion/extension angle ($p<0.05$). 5F subjects were significantly lower than both 50M and 95M (n= 60). Standard deviation bars are shown.

Although there was not a significant main effect of TA, increases from 5F to 50F to 50M were observed.

There were no statistically significant effects of the independent variables, on trunk axial twist angle, in any condition.

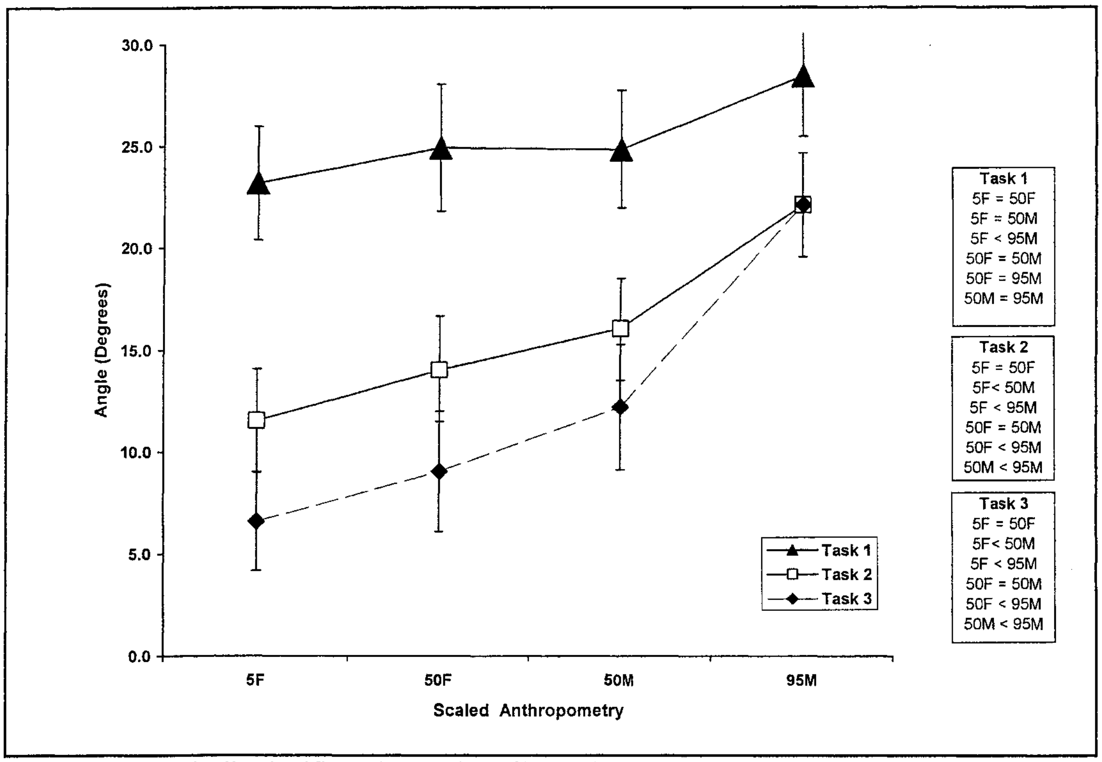


Figure 15. Statistically significant interaction effects of SA x Task for trunk flexion/extension angle ($p<0.0001$) ($n=20$). Standard Error bars have been presented.

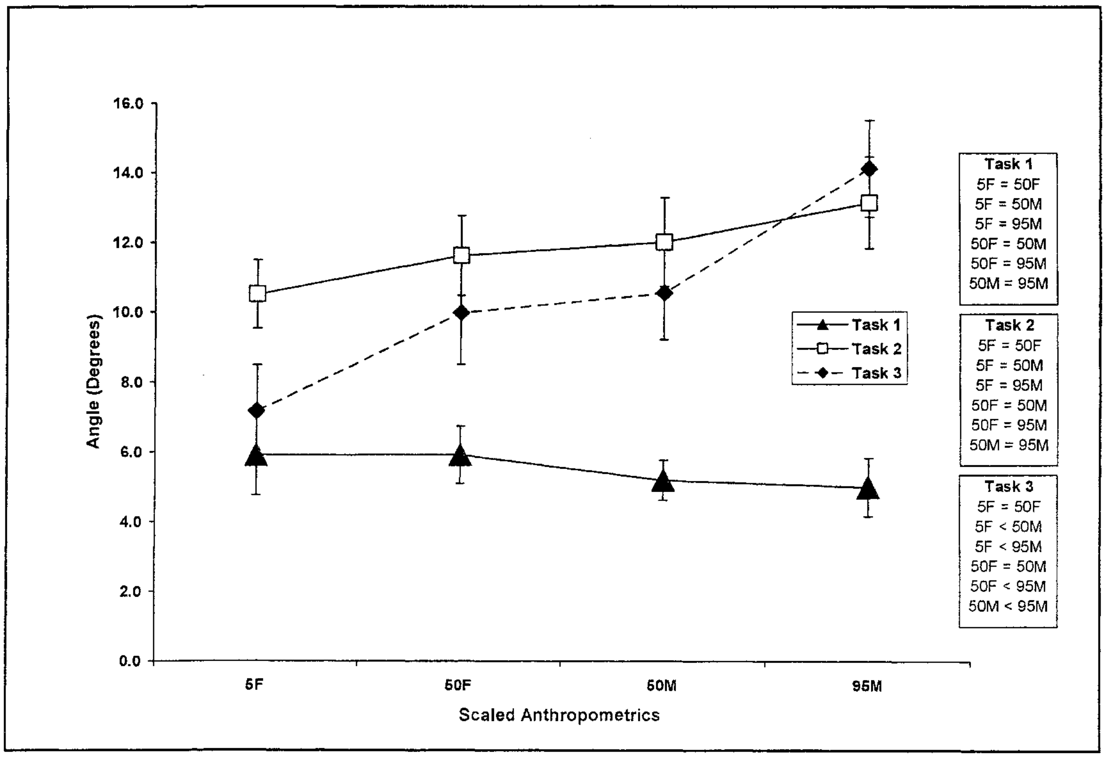


Figure 16. Statistically significant interaction effects of SA x task for trunk lateral bend angle are shown in this figure ($p<0.001$) ($n=20$). Significant differences were found for task 3 only. Standard Error bars have been presented.

Upper Limb Postures

A significant interaction between TA and Task was found for the right elbow angle. This effect was present for Task 3 only. Differences appear to be fairly systematic, such that 5F were similar to 50F, and 50M were similar to 95M, but all other comparisons were significantly different. The largest difference was noted between the TA=5F and TA=50 M, with 5F being times higher (Figure 17).

For the left elbow, an interaction between TA and SA was found. Perhaps the most noteworthy differences were observed between TA=50F compared to TA = 5F, 50M or 95M, when each was scaled to SA=50F. When scaling to SA = 5F, 50M or 95M,there were no significant differences between adjacent true anthropometries (Figure 18). However, as the gap in true anthropometry increased, differences became more apparent, and there was a general tendency for elbow flexion to decrease as TA increased.

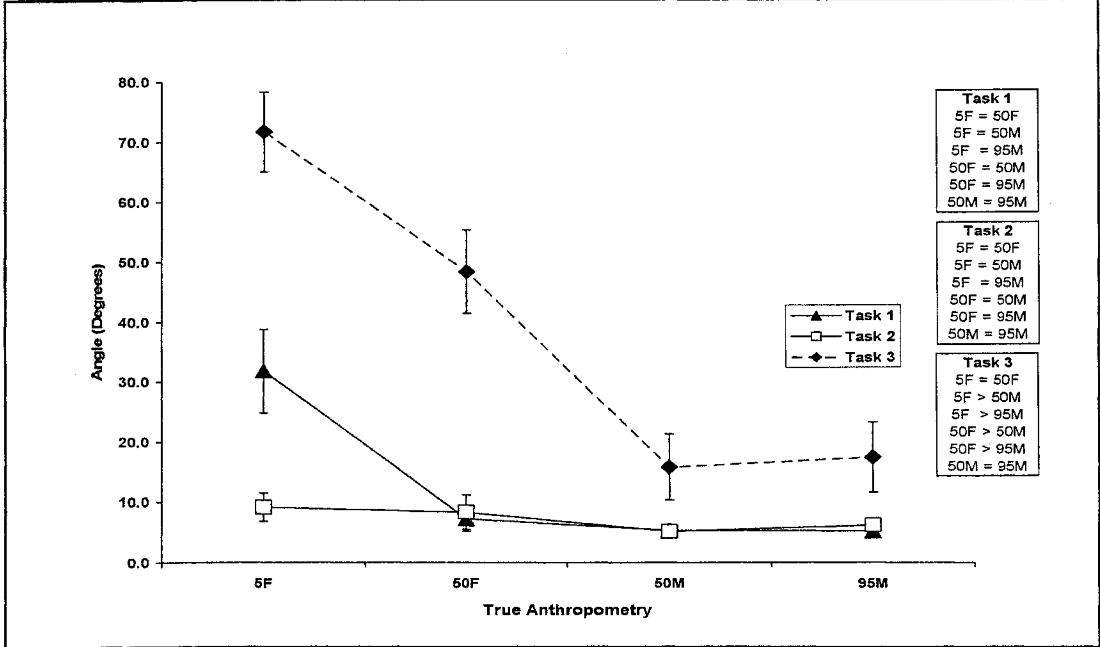


Figure 17. The interaction effect of TA x Task for the right elbow angle (n=20). Significant differences were found for Task 3 only ($p<0.01$). Standard Error bars have been presented.

A second interaction effect was found for the left elbow; between SA and Task. However, significant differences were noted only for Task 3 (Figure 19). The largest difference was between SA = 5F and 95M (85%) followed by that between SA = 5F and 50F (43%).

For the right shoulder adduction/abduction angle, a 3-way interaction between TA, SA and Task was found. For the most part, subjects performed the same during Task 2, however a 42% significant difference was noted between the performances of TA=50F / SA=5F compared to TA=5F / SA=5F (Figure 20).

In general, for Task 3, the 2 male groups do not differ and the 2 female groups do not differ when scaled in virtual reality, it is only when comparing groups with larger gaps in anthropometry, that significant differences are seen (Figure 21). Note, however, that this did *not* apply in two cases; a) for SA= 5F, TA=5F (unscaled) had right shoulder angles that were 27% smaller than TA=50F and, b) for SA=95, TA=50M had right shoulder angles that were 32% lower than TA=95M (unscaled).

A main effect of TA was found for left shoulder adduction/abduction angle. Further post hoc testing was completed, but revealed no statistically significant differences. This is not surprising, however, given that the reported ‘p’ value for this effect was 0.0447. Despite the fact that statistical significance was not found, differences can be clearly observed in Figure 22. The largest difference was found between the TA = 5F and 95M conditions, such that adduction/abduction angles were 50% greater for TA=95M.

There was also a main effect of Task for left shoulder adduction/abduction angle. Subjects were found to have significantly higher angles during Task 1 than when performing the other two tasks. Angles during the hose insertion (Task1) were 96% greater than for installing the intermediate shaft (Task2) and 60% greater than for the electrical connection to the centerline antenna (Task3) (Figure 23).

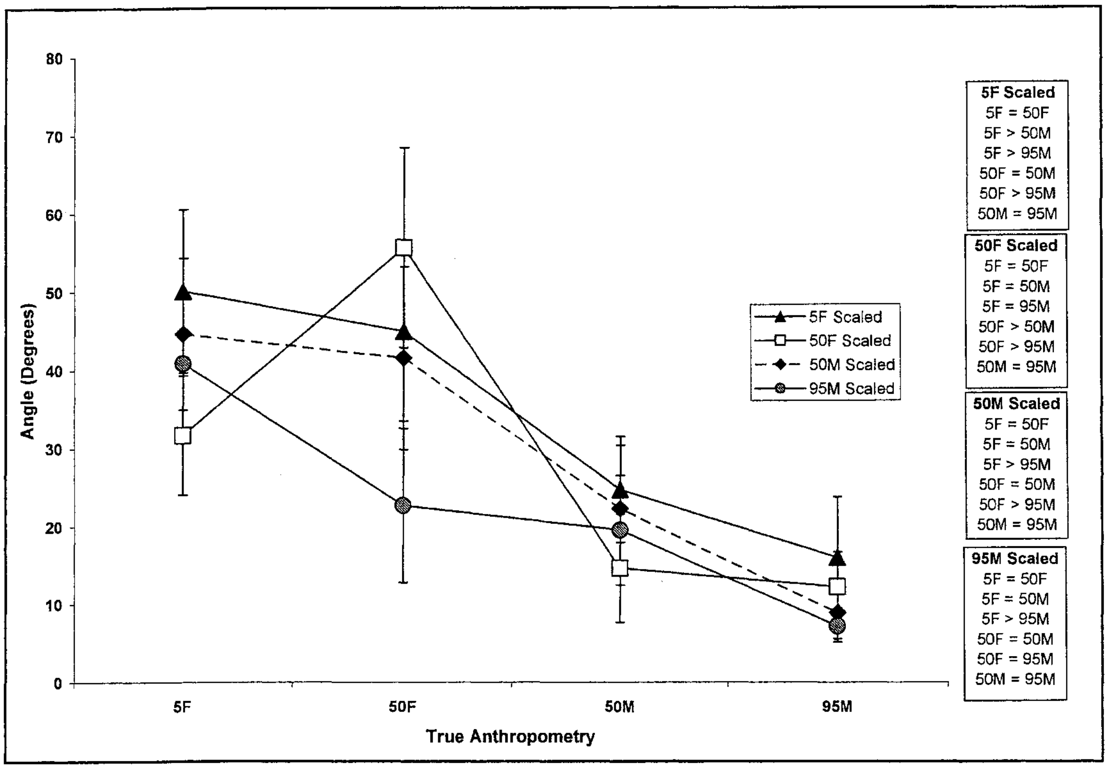


Figure 18. Interaction effect of TA x SA for the left elbow angle ($p<0.05$)($n=15$). Standard Error bars have been presented.

Resultant Peak and Cumulative Shoulder Moments

Moments for humeral rotation, anterior/posterior rotation and adduction/abduction have been combined and data are presented as a resultant shoulder moment.

Cumulative Shoulder Moments

A main effect of TA was found for the cumulative resultant moment of the left shoulder joint (Figure 24). TA=50 M was 62% higher than TA=5F and 45% higher than TA=50F.

A main effect of SA was found for both left and right cumulative shoulder moments (Figure 25). This was a fairly linear effect such that, as SA increased, so did cumulative moment. When compared to SA=5F, shoulder moments for SA=95M were 68% and 59% higher for the right and left shoulders, respectively. This finding mirrored the pattern observed for the main effect of cumulative low back loading.

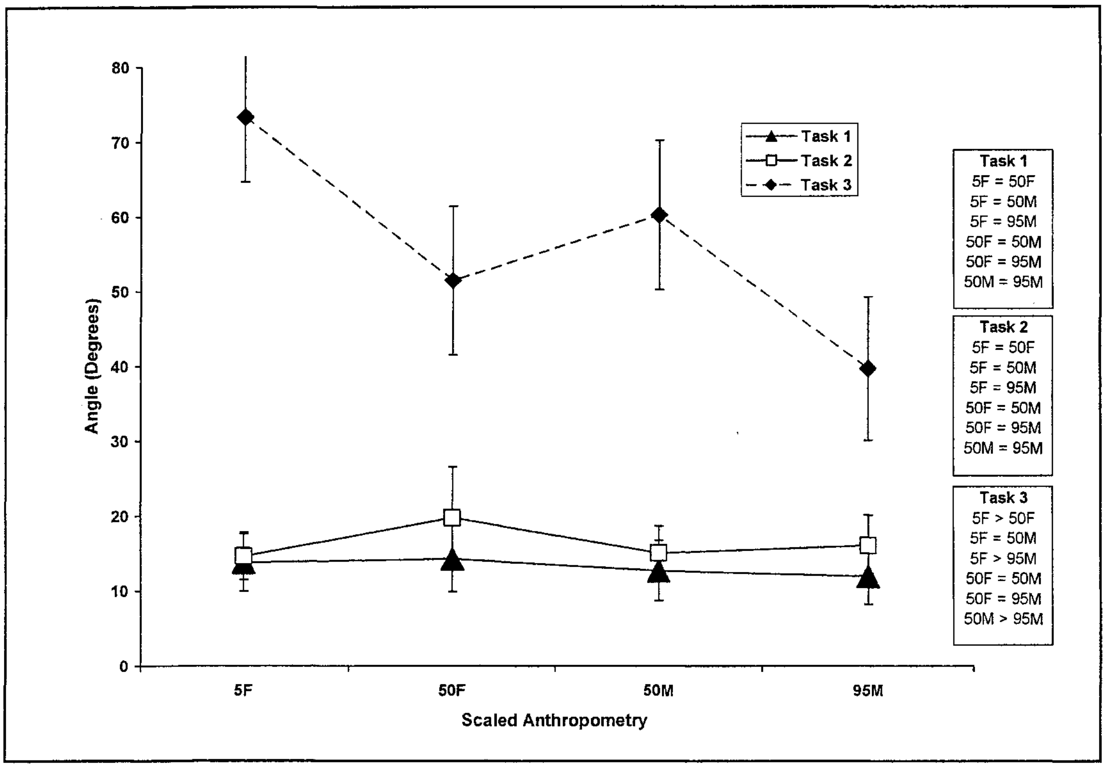


Figure 19. Interaction effect between SA and Task for the Left Elbow Angle ($p<0.0001$). Differences were noted for task 3 only (n=20). Standard Error bars have been presented.

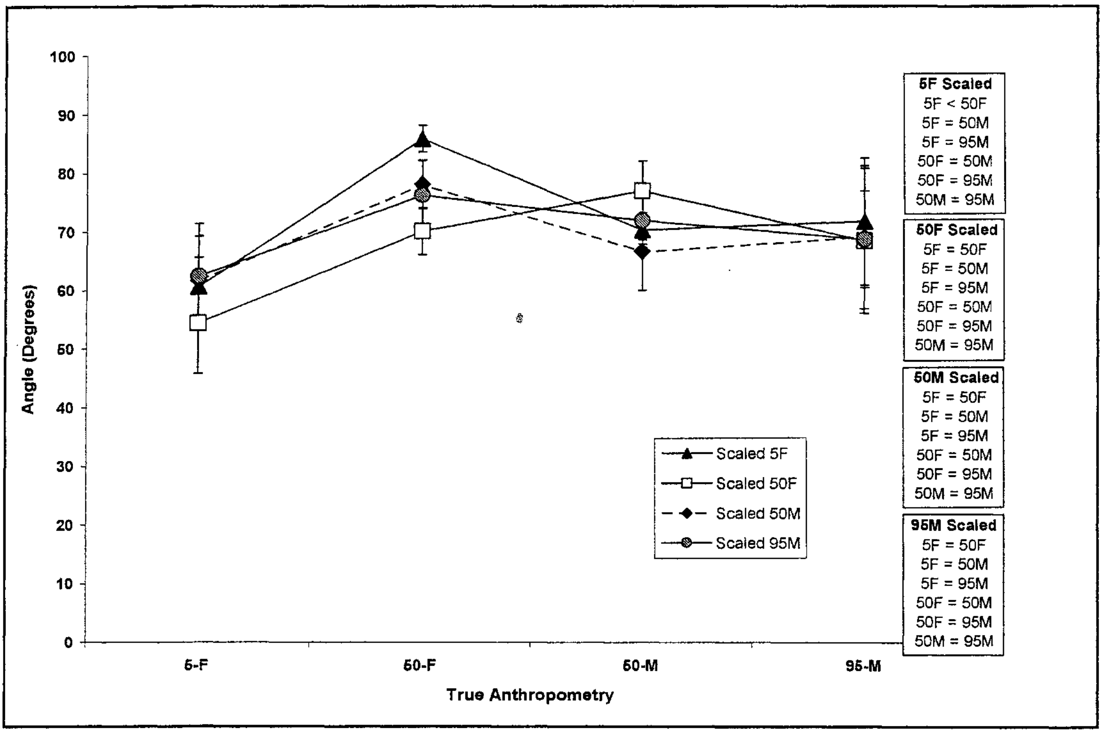


Figure 20. A 3 way interaction between TA, SA and Task was found for right shoulder adduction/abduction angle. Post hoc results for task 2 are presented ($p<0.001$) ($n=5$). Standard Error bars have been presented.

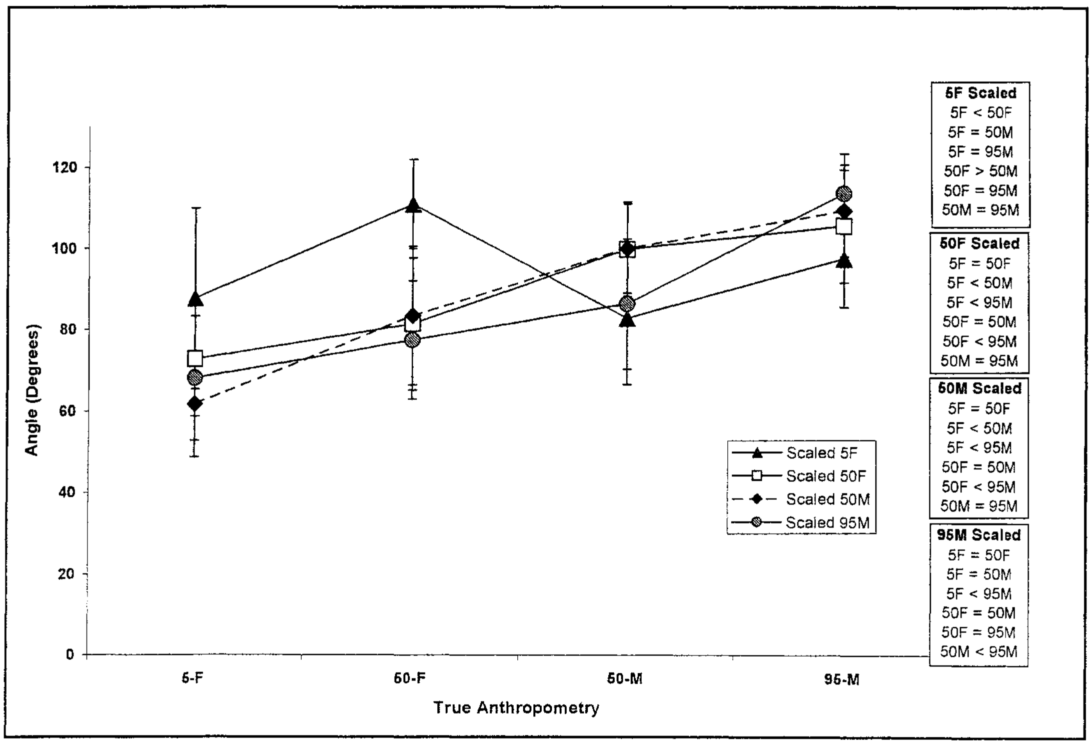


Figure 21. A 3 way interaction between TA, SA and task was found for right shoulder adduction/abduction angle) ($p<0.001$). Post hoc results for task 3 are presented ($n=5$). Standard Error bars have been presented.

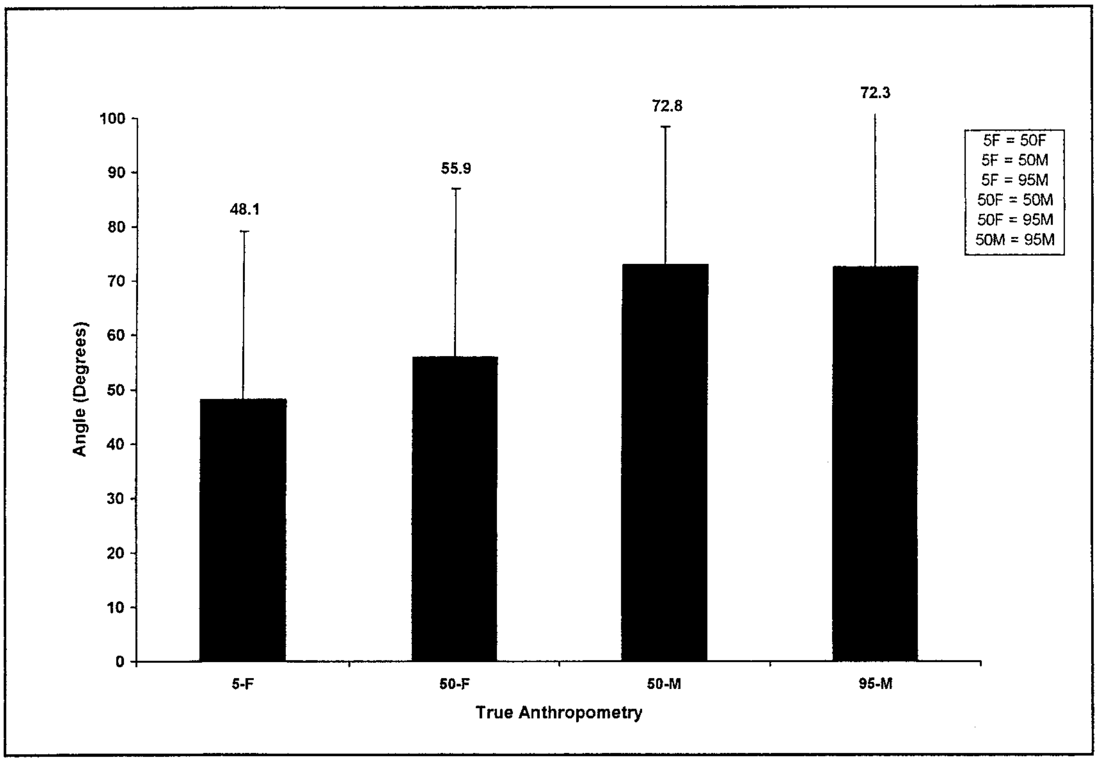


Figure 22. Main effects of TA for left shoulder adduction/abduction ($p<0.05$). However, post hoc analyses revealed no differences between individual means. ($n=60$). Standard deviation bars are shown.

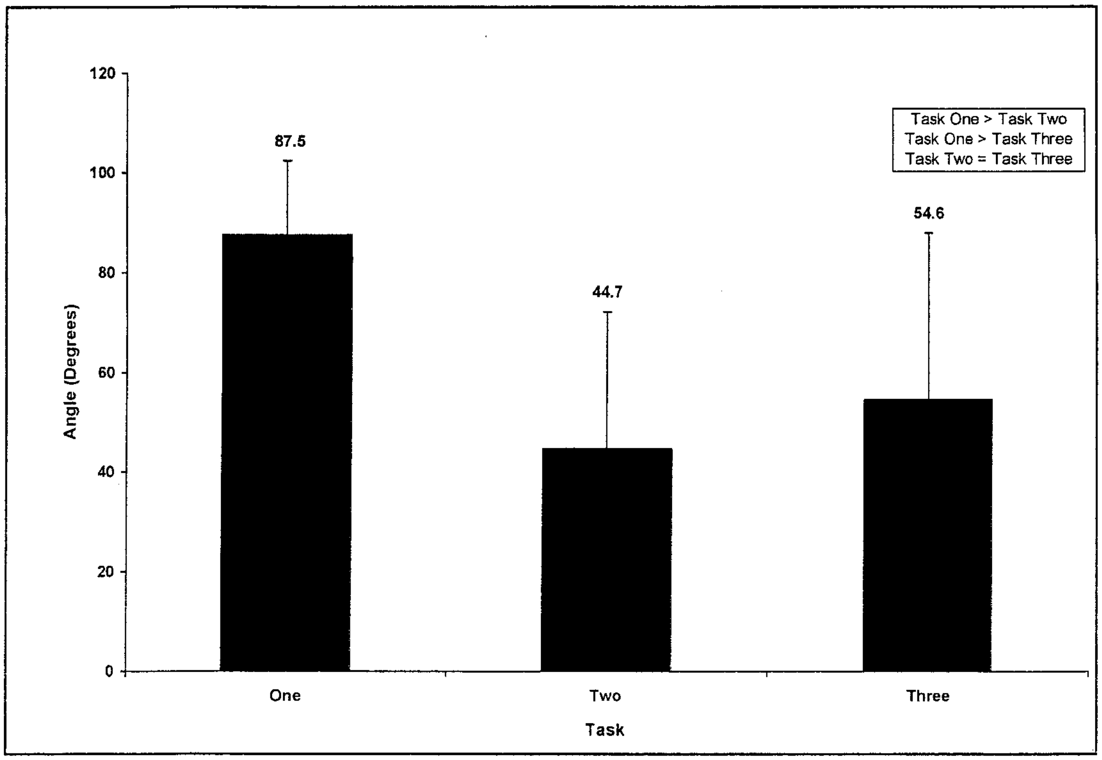


Figure 23. Main effect of Task was for left shoulder adduction/abduction angle

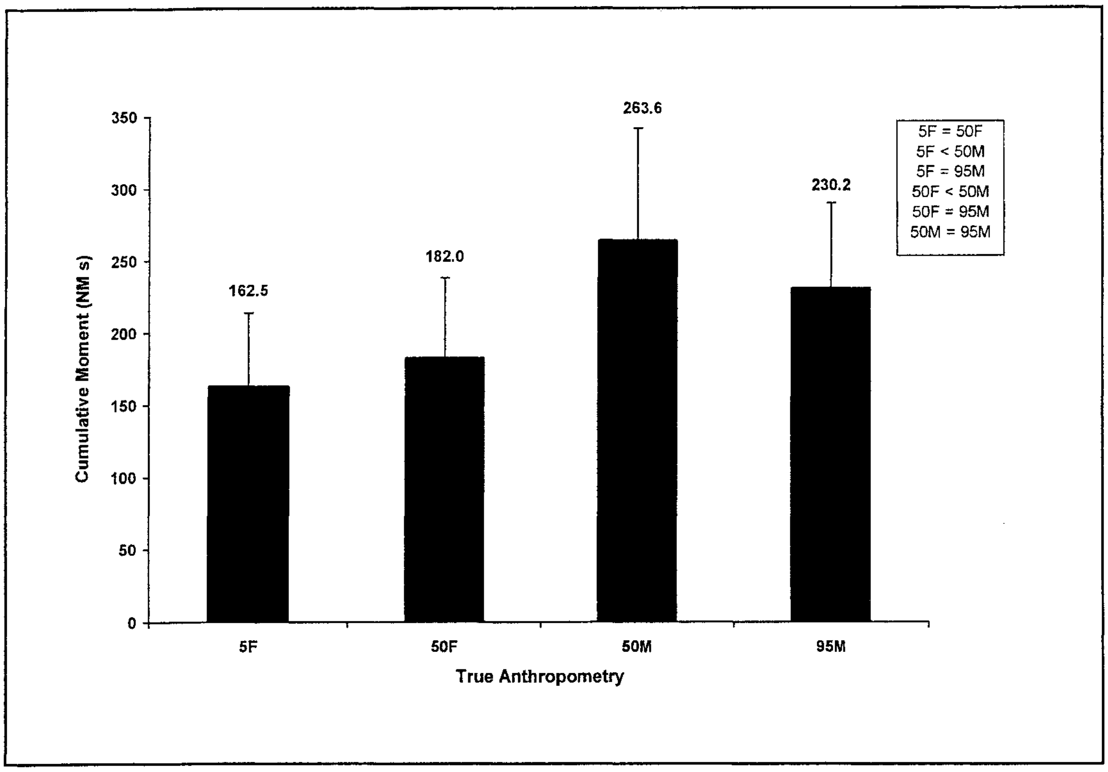


Figure 24. The main effect of TA for left cumulative shoulder moment is shown above ($p<0.01$) ($n=20$). Standard deviation bars are shown.

Peak Shoulder Moments

A main effect of TA was found for peak left shoulder moment. TA=95M was found to be 63% higher and TA=5F and 44% higher than TA=50F (Figure 26). A significant interaction was found between SA and Task for the right peak shoulder moment. There were significant differences for Task 3 only. Although significance was found for this interaction, it should be noted that no two groups varied by more than 18%.

A significant interaction was found between SA and Task for the right peak shoulder moment. There were significant differences for Task 3 only. Although significance was found for this interaction, it should be noted that no two groups varied by more than 18%.

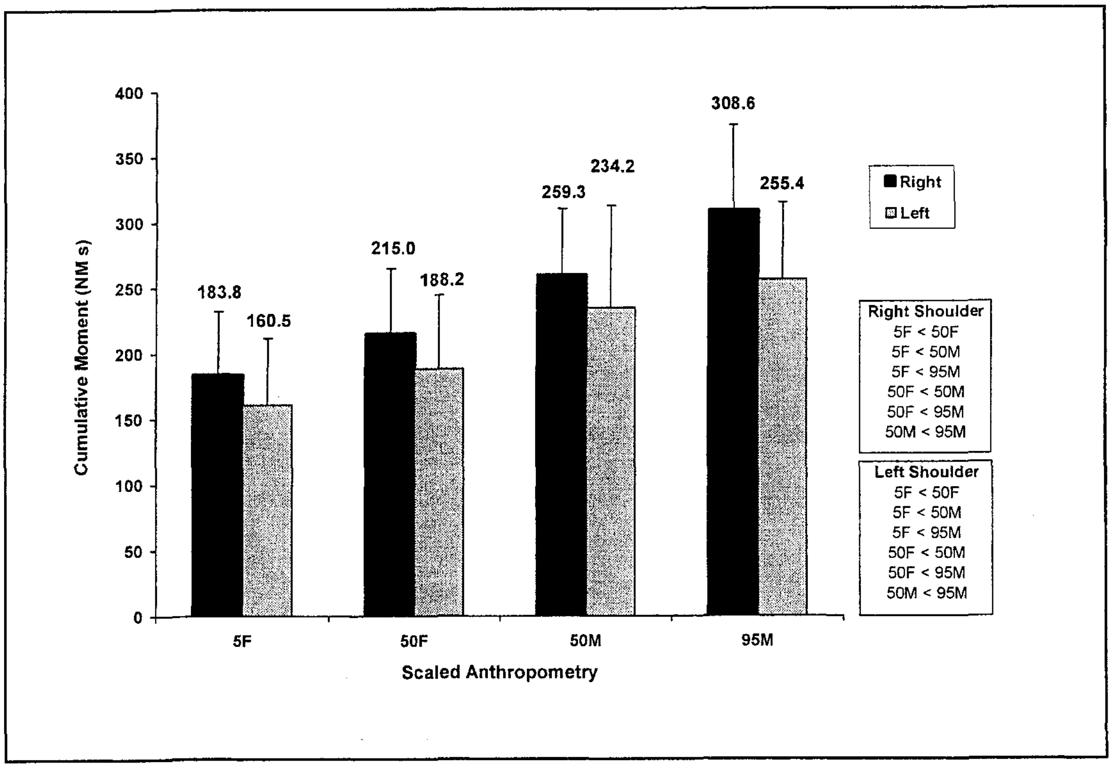


Figure 25. Main effect of SA for left and right cumulative shoulder moment ($p<0.0001$) ($n=20$, for each shoulder). Standard deviation bars are shown.

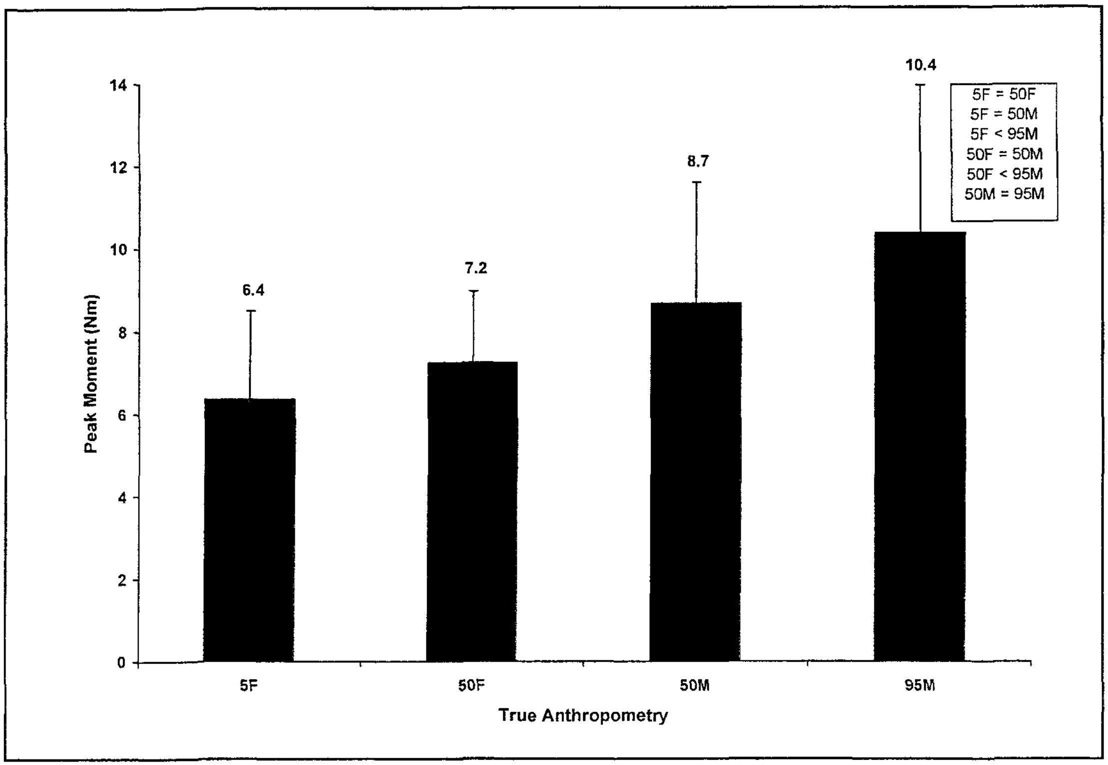


Figure 26. Main effect of TA for left peak shoulder moment ($p<0.01$) ($n=60$). Standard deviation bars are shown.

V. DISCUSSION

This study was designed to test the assumption that scaling subjects during virtual ergonomic analyses would lead to the same ergonomic decisions being made when using a subject scaled to a certain size versus using a larger or smaller subject and scaling them to represent that size. This assumption is put into practice on a daily basis within sectors of the North American automotive industry, even though no concrete evidence exists to prove that it is a sound practice. In an effort to provide direction to the automotive industry, a study was designed using motion capture technology and a virtual vehicle assembly environment. Automotive employees performed a series of assembly tasks in a virtual reality environment while data were recorded using a motion tracking system. These data were later assessed using the Jack Classic human simulation software. The main finding of the study was that a tendency to be different was noted for peak and cumulative low back loading when 5F subjects were scaled in virtual reality to represent a larger person. In general, true 5F subjects tended to have lower load magnitudes than did true 50F, 50M and 95M, irrespective of what size subjects they were scaled to represent. When assessing resultant peak and cumulative shoulder moments, the two female groups differed significantly from the two male groups.

PEAK AND CUMULATIVE LOW BACK COMPRESSION

The primary purpose of the study was to determine how each of the true anthropometry groups performed across scaled conditions in virtual reality. Results show that, in terms of peak and cumulative low back loading, there were no significant differences between the groups when scaled to the four sizes. However, it was observed that TA=5F subjects tended to have lower peak and cumulative load magnitudes than did any other group. (Figures 10 and 11). Consider, for example, when subjects were scaled to SA=95M in virtual reality, the average peak compressive force of TA=5F was 3268N and for TA=95M it was 3409N. While this was statistically not significant, these results would have generated two different conclusions during an ergonomic assessment. The NIOSH Action Limit suggests that low back compressive forces exceeding 3400N are associated with an increased risk of injury (NIOSH, 1981). This guideline is used by Ford Ergonomists when assessing the feasibility of a workstation design. If a true 95M subject had been used in a virtual assessment, it would have caused the ergonomists to conclude that the task was potentially unacceptable and they would have requested a change be made. However, had a true 5F subject been scaled to a 95M, the compressive force observed would have been below the NIOSH action limit, and the task would have been considered acceptable. In this example, the ergonomists responsible for evaluating the task would have made an incorrect decision as a result of scaling, thereby putting true 95M operators at risk when performing this job. It is important to note that if a 50F or 50M had been scaled to represent the 95M, the compressive forces for these groups (3436N and 3578N, respectively), would have led an ergonomists to make the same decision as when the true 95M had performed the task.

These findings suggest that, if an ergonomic assessment is being performed in virtual reality, 5F subjects should not be scaled to represent a larger person, as the potential to make incorrect ergonomic decisions about peak and cumulative forces on the low back is increased. Overall, 5F subjects almost always had lower compressive low back forces. In fact, there was only one scenario where the 5F did not have the lowest compression value. When both were scaled to SA=5F, the average cumulative load of the TA=50F subjects was slightly less than for TA=5F. However, in all other cases, peak and cumulative compression showed a tendency for the TA=5F to be lower than the other true anthropometry groups. This suggests that, when interested in the low back demands of a 5F, a true 5F should be used to conduct the virtual ergonomic assessment. Similarly, if interested in the demands for a 50F, 50M or 95M, a 5F subject cannot be scaled in virtual reality and expected to generate the same results. It would however, be acceptable to scale anthropometry between the 50F, 50M and 95M groups and be confident that the same ergonomic decision would be made. While the results for peak and cumulative low back compression did not yield significant differences between groups, there was relevant information within the data could not be ignored. It is anticipated that, if the study was increased to include a larger sample size, significant effects of TA might be expected.

There has been a significant amount of research dedicated to establishing threshold limit values for peak compressive forces on the low back. As mentioned above, the NIOSH Action Limit of 3400 N was adopted by Ford as an ergonomic guideline for ensuring assembly jobs fall within safe exposure limits for peak low back compression. The peak compressive forces resulting from tasks performed in this study varied considerably, depending on the scaled anthropometry. When subjects were scaled to a 5F, compression ranged from 815 N to 2197 N. For 50F a similar range was observed (873 N to 2875 N). When scaled to the 50M and 95M compressive forces were between 1382-3884 N and 2030-5265 N, respectively. This shows that tasks were not considered risky for either female group. However, as the size of the subject increased, the compressive forces also increased. Mital et al. (1993) also proposed guidelines for exposure to peak low back compression. It was suggested that female and male compression limits should be 2700N and 3900N, respectively. If tasks from the current study are compared with these guidelines, when scaled to a 5F or 50F, one subject exceeded the limit of 2700N and this was during the antenna electrical connection task. When scaled to represent 95M, 12 of 20 subjects exceeded the 3900 N guideline when performing the antenna electrical connection.

Norman et al. (1998) calculated the compressive low back forces of automotive assembly workers. They found that those who were classified as a case-subject for low back pain had experienced 21.0 MN s of exposure over the period of one work shift. Control subjects experienced 19.5 MN s of cumulative low back compression. If data from the current study is averaged across all subjects and conditions and extrapolated out to represent a full work day (7 hours), cumulative compression was equal to 38.9 MN s. This is considerably higher than what was found by Norman et al (1998) however, the methods used to calculate cumulative compression were quite different, making a direct comparison difficult. The current study utilized the technique of rectangular integration where as the Norman study used peak static loads calculated for a task and multiplied this value by the task time.

PEAK AND CUMULATIVE RESULTANT SHOULDER MOMENTS

Results for left peak shoulder moment showed that SA = 5F and 50F had peak left shoulder moments that were significantly less than for SA=95M. With respect to cumulative shoulder moments, scaling to both female groups resulted in smaller moments than with SA=50M for the left shoulder. While not significant, the data for cumulative moment show that, compared to the SA=5F or SA=50F, loads for the SA=95M were 42%

and 26% higher, respectively. It is likely that, if the sample size had been larger, these differences may have also become significant.

If the results of both peak and cumulative moments are considered together, the data suggest that, when scaling subjects in virtual reality, TA=5F and TA=50F subjects can be expected to yield the similar results. The same is true when comparing results from TA=50M and TA=95M, however, male and female groups differed too much from one another to conclude that scaling between them is acceptable. Based on this information, it seems reasonable to suggest that if interested in the outcome of a virtual assessment for someone who is a 5F or 50F, it is acceptable to scale subjects within that range. The same holds true when interested in the results of a 50M or 95M, subjects within this range can be scaled in virtual reality. Scaling outside of these parameters presents the risk of generating results that differ from what would be expected if the study was performed with an unscaled subject of the appropriate size.

The range of peak resultant shoulder moments observed in this study varied from 3.4 Nm for TA=5F to 20.1 Nm for TA=95M. The average shoulder moment for all 3 tasks (hose insertion, intermediate shaft and antenna electrical connection) was 9.4 Nm. The population strength data available in Jack shows that the maximum strength of the male shoulder joint is 128 Nm for the right and 119 Nm for the left. Average female strength data indicate that the shoulder is capable of generating 66 Nm (right) and 61 Nm (left). If these values are compared to the demands of the study tasks, it can be seen that all tasks were well below the maximum strength limits for both the male and female populations. In, fact, even the maximum observed resultant male shoulder moment (20.1

Nm) was only 16% of the strength capability of the right male shoulder joint. The maximum moment observed among women was 18.9 Nm, or 29% of maximum.

KINEMATIC DATA

Five of the 7 segment angles collected showed significant main effects of TA. Included are trunk flexion/extension angle, right and left elbow angles as well as right and left shoulder adduction/abduction angle. These findings will be discussed below.

The main effect of TA for trunk flexion/extension showed that scaling between 5F and the other three groups did not yield the same results. This is not surprising given that the percent difference between the height of a 5F and the 50M or 95M was 15% and 23%, respectively. Fifth females had lower flexion/extension angles than did either of the male groups, regardless of the size they were scaled to. With practice, humans become very good at minimizing their job demands to conserve energy, reduce pain, decrease unnecessary muscular activity, etc (Alexander, 1997). It is possible that, in an effort to minimize the compressive forces on the low back, small females opted to move their upper body closer to the end goal by rotating about the pelvis while maintaining a more neutral spinal posture, which would have accounted for the lower peak compressive forces and lower trunk flexion angles for 5F. Given that on the true assembly line, small subjects are faced with greater reaching challenges than are taller subjects, it is plausible that shorter subjects have become very good at performing tasks in a manner that imposes the least physical demands on the body. When scaled to represent 5F or even the 50F, taller subjects would have had less opportunity, than the short subjects, to learn a reaching strategy that imposes minimal physical demands on the body. Shorter subjects, on the other hand, have had a wealth of experience and time to develop a conservative reaching strategy, which may be to move the pelvis as opposed to the spine. During the study, taller subjects would have been required to leave the reach zones, for which they are most accustomed, more often than short subjects. When shorter subjects were asked to perform as a 5F or 50F, the reaching demands would have been very similar to their real life working scenario and, therefore, were not likely to be perceived as a new challenge.

The results of this study only allow for the above hypothesis about *why* different anthropometric groups performed differently in terms of trunk flexion angle. However, the most important finding is that small females and large males *do* perform differently in virtual reality even if they have been scaled to the same size. Further investigation of additional outputs available through the Jack Task Analysis Tool Kit reports could assist in understanding if the hypothesis presented above accurately reflects the differences seen in trunk flexion/extension angles between short and tall subjects performing in virtual reality. In particular, the degree of pelvic rotation at the point of peak compression could be tested for significant differences. Furthermore, shear forces at the low back could also be reviewed. Presumably, if shorter subjects had chosen to rotate about the pelvis, as opposed to flex at the spine, higher shear forces would have been observed for these subjects. Given that the L4/L5 spinal segments would not be as severely flexed, compression at this joint would be somewhat alleviated during pelvic rotation. Furthermore, due to the gravitational forces acting on the joints in an anterior direction, it would be expected that shear forces would be higher when the pelvis is rotated as opposed to when the trunk is flexed. It is important to emphasize that these postulations, to explain *why* subject groups may have used different postures for the same condition, are based on observations from the current study and cannot be confirmed without further investigation.

In general subjects tended to use their right hand to execute one handed tasks (Task 2; intermediate shaft install and Task 3; electrical connection to antenna), and those who chose to support portions of their body weight with a lean, typically did so with the left hand. The data for shoulder adduction/abduction angle shows that differences for TA were found for the right shoulder only. For installing the intermediate shaft (Task 2) a significant difference was found between the performances of 5F scaled to 5F, compared with 50F scaled to 5F. However, if the data are further examined (Figure 20) it can be seen that all subjects performed Task 2 in a similar fashion and that even TA=50F group followed the same pattern as other subjects when scaled across the different sizes. Thus, although the significant findings for Task 2 should not be disregarded, it is possible that this one difference was, in part, due to the relatively small sample size of each group.

For Task 3, the right shoulder adduction/abduction angle seemed to be fairly sensitive to the effects of scaling, where several differences were found between groups as close in size as the 5F and 50F or 50M and 95M. The same was true for right elbow angle during Task 3. However, in this case, the two shorter female groups were both different than the two taller male groups, but there were no differences within the genders. From an observational stand point, the most variability in performance was seen during Task 3 (electrical connection to the centerline antenna). There were multiple methods possible for performing this task; some ducked under the roof of the car, others stayed outside the vehicle and reached in with their arms only. Regardless of technique, subjects could have also chosen to lean on the top edge of the door frame or on the side of the door, or not to lean at all. These findings suggest that, as the task becomes more complex or presents more options for execution, the ability to scale subjects in virtual reality is reduced. As mentioned, a potential explanation for this finding is that shorter subjects are more skilled, due to practice, with demanding reaches and have thus developed a more conservative reaching pattern as compared with larger, unpracticed subjects. This hypothesis is, in part, confirmed by the data that can be observed in Figure 22 where, regardless of what size they were scaled to, true small females tended to have adduction/abduction angles that were closer to neutral than did the larger males. Again in Figure 18 it can be seen that elbow flexion was always higher for shorter subjects, which would have acted to decrease the moment arm of the upper limb (where 0 degrees is full extension and 180 degrees is fully bent). The taller males had their elbows closer to full extension, thereby increasing the length of the upper limb and, thus, the moment generated about the shoulder joint. This tendency, which points towards smaller females minimizing the demands at the shoulder joint, is similar to what was observed for the trunk flexion/extension angle.

Significant differences were also noted for the left elbow angle, across all three tasks. Regardless of how subjects were scaled, the TA=5F group was always more flexed at the elbow than the TA=95M group. Additional differences were observed between TA=50F and both 50M and 95M but, in general, it can be said that the likelihood of performance differences increased as the gap in true size increased. Given that the left arm was used primarily to lean during a task, this may suggest that leaning strategies cannot be replicated when considerable differences in true anthropometry exist.

TASK SELECTION

A main effect of task was observed for 8 of the 13 dependant variables, including peak low back loads, peak right shoulder load, trunk flexion/extension and lateral bend angles as well as the elbow and shoulder angles for both arms (Appendix E). When tasks for this study were originally selected, the researcher sought to select activities that would represent a range of jobs performed on the plant floor as well as tasks that presented more than one potential execution strategy. The purpose of choosing tasks with multiple potential execution methods was to ensure unbiased results when assessing the variability in performance of multiple subject anthropometric groups in different conditions. The goal of selecting a range of tasks from the plant floor was to ensure the results of this study were applicable to multiple processes and jobs within the automotive industry. The fact that significant differences were observed between tasks for more than 60% of the dependant measures, confirms that the researcher was successful in choosing a diverse set of tasks for this study. If all tasks had placed the same demands on subjects, it would be very difficult to apply these results with any level of confidence to tasks that were not as similar. This does not suggest that results can be generalized to processes outside of automotive assembly without caution. This would include cascading the results to automotive stamping applications, maintenance operations or tasks found within other industries. What can be stated, however, is that the present results do reflect a range of processes found in final vehicle assembly facilities. Given that the automotive partner for this research is responsible for assembly plants specifically, this data will fit their needs adequately.

HYPOTHESES REVISITED

> *1. When a small female (5F) is scaled to represent a large male (95M), significant differences ($p<0.05$) will exist in the results of a peak and cumulative low back compression assessment. The same will hold true when a large male is scaled to represent a small female.*

No significant differences were observed between the small females and large males for peak or cumulative low back compressive forces, and therefore the alternative hypothesis has been rejected. Although no significant differences were found for measures of peak and cumulative forces, it should be noted that there was a tendency for 5F to have lower peak and cumulative low back compression magnitudes than did any other subject group.

> *2. No significant differences ($p<0.05$) will be observed in the results of a low back assessment of peak and cumulative compression between the 5th percentile female and the 50th percentile female when they are scaled to represent one another. The same is expected when comparing the 50th percentile male and the 95th percentile male.*

No significant differences were found between 5F and 50F, or between 50M and 95M. Thus, there was a failure to reject the null hypothesis. As mentioned previously, differences for TA=5F and TA=50F were observed for both peak and cumulative low back loading. It is possible that with further investigation and a larger sample size, the research may have found significant differences, in particular between the 5F and 50F groups.

> *3. Effects of the TA variable will be smaller for low back cumulative compressive forces compared to peak forces.*

There were no significant effects of true anthropometry for either peak or cumulative compression when subjects were scaled in virtual reality. There was a significant effect of both peak and cumulative compression. When increasing from the 5F to 95M, the progressive increase in cumulative load was 41% (from 5F to 50F), 33% (50F to 50M) and 53% (from 50M to 95M). For peak loads it was 26% (from 5F to 50F), 40% (50F to 50M) and 37% (from 50M to 95M). The data did not support the hypothesis.

LIMITATIONS AND ASSUMPTIONS

Subjects used in this study were employees of the Ford pilot plant, which is where the first physical prototype of each new vehicle is produced. Because the volume of vehicles exiting this facility is much lower than a normal full production assembly plant, there are some differences in the way operators interact with the vehicle. For example, as opposed to a traditional moving assembly line, the vehicles in the pilot plant are placed on stationary skids and the operators must move from workstation to workstation to get to each vehicle. In a normal assembly plant, the vehicle travels on a pulley or conveyor system to the operator. Workers in the pilot plant may be responsible for performing 10 or 20 different assembly processes on the same vehicle as opposed to the same process on multiple cars, thus a work cycle duration in the pilot plant is usually much longer than in a typical assembly facility. These differences suggest that, although workers in the pilot plant are involved with assembly operations, their typical work day is structured differently than the majority of vehicle assembly operators. Despite these differences, the current study assumed that results derived from pilot plant assembly workers can be generalized to workers in other assembly plants. In an attempt to minimize any potential differences between pilot plant workers and normal assembly plant workers, all subjects were recruited from the shop floor within the pilot plant, meaning that office workers, maintenance crews and tradesmen were excluded. Therefore, it was guaranteed that all subjects had been exposed to assembly activities. Furthermore, workers in the pilot plant are generally recruited internally from full production assembly plants. Therefore, all subjects in the study had past experience with regular production facilities.

In this study, the researcher chose to use a wall mounted projection to display the virtual environment during data collection. The other alternative, which is often employed in virtual reality and human simulation labs, is the use of a head mounted display unit. This apparatus is worn by the subject during data collection and the environment is viewed in first person. Alternatively, in this study, subjects were asked to focus on the wall image during data collection. This image was also projected in first person but was located at a distance away from the subject's eyes. While both options were available to the researcher, certain limitations were associated with each method. For example, comfort and picture resolution were the two main concerns associated with using a head mounted display unit. The Work Center for Human Simulation has rarely used their head mounted display unit because the quality of its image is poor relative to what can be projected on a wall. Also, there had been considerable complaints from past subjects that the head mounted display unit was uncomfortable and they often had to hold it in place with their hand. Given the time period that the current subjects were immersed in virtual reality (1 to 1.5 hours), it did not seem reasonable to ask subjects to wear an uncomfortable piece of equipment. Furthermore, there was a fear that subjects may alter their usual movement patterns in an attempt to reduce sliding and shifting of the unit on their head, which could have potentially had an effect on the final results. For these reasons, a wall projected image was chosen. While this was considered the best option for this study, and subjects were encouraged repeatedly to watch the image on the screen, there may have been a tendency to rely more on the physical props than if a head mounted display was used.

During data collection, it was observed that subjects tended to support part of the body weight by leaning on a surface while executing the three tasks. However, because they were encouraged to perform tasks in the most comfortable and natural way possible it was not possible to collect leaning hand forces. There were multiple locations that subjects could have chosen to lean, and placing a force gauge at each location was not practical or feasible. To counteract this gap in the data collection, the researcher reviewed all data post-collection to determine where subjects tended to rest their hands. Based on this information, a sub-study was conducted, where a mock up of the original props was built and subjects were asked to generate the same postures while the loads in the supporting hands were recorded using a force plate. These data were very consistent across SA and TA as a percentage of body weight. In fact, given that no significant differences were observed between the groups, the same percentage of body weight could be applied for 5F, 50F, 50M and 95M subjects. These measures were used to estimate the forces seen at the supporting hand during original data collection. In the absence of true hand load measures, data collected from the sub-study are believed to be the best estimate of the forces observed at the hands for the three tasks studied.

IMPACT TO INDUSTRY

The Assembly Ergonomics division of Ford Motor Company has recently expressed a need to review tasks from the perspective of cumulative loading. This interest was generated based on a gap in the assessment tools available to the company. Jobs existed on the plant floor that intuitively appeared to be unsafe, but none of the ergonomic assessment methods could clearly identify the risks. For example, processes that involved sustained awkward trunk postures were being flagged by ergonomists based on operator complaints, but the assessment tools available at Ford did not seem sufficient to review such tasks. Cumulative low back loading seemed to be a logical variable to review, however there is very little published literature to support a guideline for acceptable exposure. In fact, to date, there is one study that is directly applicable to the automotive industry. Norman et al (1998) collected data from a large sample of North American automotive assembly workers and subsequently published a tool that could be used to assess cumulative loads and that provided feedback (odds ratios) about the exposure levels. While the subjects and the job types used during Norman's study are ideal for the auto industry, it has been shown that their method of calculating cumulative loads may not be as accurate as other proposed methods (Callaghan et al, 2001). Calculating cumulative low back loads via rectangular integration has been shown to be more accurate than the square method used by Norman et al (1998) (Callaghan et al, 2001). Summation of the loads using rectangular integration was the method of choice for the current study (30fps). The Jack Classic Toolkit provides this data within minutes following the post-processing of motion capture data, thus making the collection and analysis of large amounts of cumulative low back loads more feasible than any other method known by the researcher. Agnew et al, (2003) also used a motion tracking device and a biomechanical model to assess cumulative loads during a lifting task. However, the benefit of the current method is that data is obtained and reported in 3 dimensions, whereas the method of Agnew et al (2003) was only applicable to work in 2D.

This study has shown that the collection and assessment of cumulative low back loading, using motion capture and virtual reality, can be done quite quickly and easily, relative to more traditional methods. Specifically, knowing that subjects between the size of the 50th F and 95th M can be used to represent one another and produce similar results for low back compression, allows a researcher to reduce the selection criteria for study participants, thereby speeding up the recruitment process and rejecting fewer subjects based on size. The ability to immerse subjects in a virtual reality environment and have them perform under different sized conditions, without compromising the accuracy of the results, provides the added benefit of keeping data collection within a lab environment. This allows researchers to avoid the complications associated with collecting data on a plant floor, such as acquiring plant and union approval, dealing with obstacles during data collection (ie. moving vehicles, large storage bins, etc), and also the limitation of finding equipment that is compatible with field collection. Very few motion capture technologies are suitable for the plant floor. Thus, given the need to review jobs from a cumulative loading perspective, and the traditional challenges of collecting data and recruiting a large number of appropriate subjects, these findings support the use of motion capture and virtual reality as a viable method for determining the cumulative low back loads associated with a task or job. This may, in fact, be a very suitable collection procedure for developing a large database of cumulative low back loads for a variety of different tasks. This information, in conjunction with epidemiological data could be used to help establish a threshold limit value for exposure to cumulative low back loading. The collection and analysis of large amounts of cumulative low back loading data has been a challenge to date, with the bulk of the research dedicated towards establishing a suitable methodology for this endeavor. As such, the possibility of using virtual reality may prove to be an interesting alternative for researchers.

To the best of the author's knowledge, this is the first study to address the effects of scaling different sized subjects in a virtual environment. Past research has been conducted to show that virtual assessments yield the same results as the more traditional approaches to ergonomic assessments (i.e. plant floor observations), however, the virtual studies were all designed to replicate the anthropometrics of the real life scenario, thus scaling was not a factor (Feyen et al, 2000). The ability to scale anthropometry is a readily available option within the Jack human model. This does not suggest that the developers endorse/or discourage the use of the scaling feature to alter anthropometric measures during automotive or other ergonomic assessments. However, given that the function exists, and for some users is seen as a means to reduce the time (and therefore cost) associated with conducting a virtual ergonomic assessment, the results of this study will serve as valuable information for users of motion capture and virtual reality integration.

During a virtual ergonomic assessment, the Vehicle Assembly division of Ford Motor Company considers three main criteria; a) is the job acceptable to the 5th percentile female in terms of reach, b) will the 25th percentile female have the strength to perform the task and c) is there sufficient clearance for the 95th male to access all parts? If a virtual assessment was being performed and all three criteria were to be tested, an Ergonomist would be required to do one of two things; a) recruit three individual subjects (5th female, 50th female and 95th male) and repeat the study three times OR b) recruit one individual to perform the task 3 times while scaled to represent the different sizes. In the interest of both time and money, virtual assessments have been conducted using the second option. However, to date, it has been unknown how this practice affects the validity of the results from an ergonomic assessment. Presumably, if it is not valid to assume that a subject can be scaled to any size and perform similarly to someone of that actual size, then the likelihood of making a wrong ergonomic decision is increased. The costs associated with enforcing a product or design change, when it is not actually necessary, may cost thousands to millions of unnecessary dollars. Furthermore, the cost of *not* identifying an ergonomic problem that actually exist, is also a potential concern related to unsuccessful scaling practices. This is not only associated with unnecessary cost to the company, but also places the working population at risk for an avoidable injury.

SCALING RECOMMENDATION FOR INDUSTRY

In an effort to improve the practices used in the Work Center for Human Simulation (WCHS) lab, as well as reduce the potential for unnecessary spending resulting from ineffective scaling practices, a set of scaling parameters and procedure will be recommended to Ford Motor Company based on the results of this study. What is most interesting to note is that, if one was to separate the data related to low back loads (compression) from the shoulder load data (resultant moment), and tried to answer the question; *can subjects be scaled in virtual reality and yield similar results to un-scaled subjects of the same size*, the answer would be different depending on which region of the body was the concern. The intended audience for this study is the Ergonomics division at Ford Motor Company, who are responsible for ensuring jobs are safe and acceptable to all regions of the body. Therefore, these Ergonomists will likely never be interested in using scaling guidelines that are specific to just the low back or just the shoulder individually. Rather, their concern will focus on ensuring that the scaling parameters they employ are conservative enough to encompass assessments of both the shoulder as well as the torso. Nevertheless, the Work Center for Human Simulation is a rather progressive lab and their involvement in academic research is strong. For this reason, recommendations have been provided individually, based on body part, in the event that a research study is undertaken where data will focus strictly on the low back or the shoulder. However, for the day-to-day virtual ergonomic assessments performed in the lab, a set of all-encompassing recommendations have also been provided.

When assessing the peak or cumulative demands on the low back, scaling subjects between the range of the 50F to the 95M was deemed an acceptable practice. However, because there was a tendency for the loads of the TA=5F to be lower than the other three groups, 5F subjects should not be scaled during motion capture and virtual reality integration. Furthermore, if interested in the results of a 5F, it is recommended that a true 5F subject perform the task.

In terms of ergonomic assessments related to the shoulder, if limits are to be based on 5F or 50F individuals, subjects can be safely scaled anywhere within the range of a 5F to 50F, without affecting the accuracy of the results and subsequent ergonomic decisions. If a study is being conducted, and results will be based on 50M or 95M, it is acceptable to select subjects that fall within this range and scale them to the desired size. Scaling outside of these parameters presents the risk of erroneous results.

For virtual ergonomic assessments that will focus the loading demands of the low back and shoulder simultaneously, the following scaling parameters are recommended;

When the demands of the low back and shoulder are going to be based on the either the 5F or 50F anthropometry, scaling should not be employed. In this case a true 5F or 50F subject must complete the study. If the demands of the low back and shoulder are going to be based on the anthropometry of a 50M or 95M, subjects between the range of a 50M and 95M can be scaled to represent one another without altering the results of the study.

CONCLUSIONS

Despite the fact that individuals can be scaled to *appear* smaller, there are no compensations made to help them *feel* smaller. This may in part explain why some of the differences were observed between small and large individuals. Furthermore, it is anticipated that small subjects have had considerable real-life experience performing in a variety of situations, where sometimes tasks can be performed close to the body and others are at the extremes of their reaching capability. Given that jobs at Ford are designed to accommodate the 5th percentile female in terms of reach, these tasks will inherently be easier for the tall males. It is possible that when scaled, females were able to perform using motion patterns that were more efficient and practiced given their past experiences with real life work demands. Taller males, on the other hand, were asked to perform under conditions which they have rarely, if ever, experienced on a true assembly line. This lack of practice may have led to the use of over-exaggerated movements when performing under conditions that required them to reach further than normal because they were scaled to be smaller.

Furthermore, the kinematic results of this study suggest that, as a task becomes more complex or presents more options for execution, the ability to scale subjects in virtual reality appears to be reduced. The majority of differences in segment angles were observed for Task 3, which was also the task that presented the greatest number of possibilities for completing the task. The differences in segment angles were subsequently responsible for a good portion of the variability observed in loading magnitudes for the shoulder and low back. Given that segment angles tended to vary more with complex tasks, it is expected that the feasibility of scaling is partially dependant on the activity being performed. The results of the study have been tailored to automotive assembly applications. Caution is warranted for applying these data to other industries, in particular for activities that are deemed to be quite flexible in terms of execution patterns.

FUTURE RESEARCH DIRECTIONS

The findings of this study have identified the conditions under which scaling is acceptable and unacceptable during motion capture and virtual reality integration. However, it has not addressed the question of *why* subjects perform differently. Based on the information presented, hypotheses can be generated about why subjects utilize different movement strategies, even when their environment is made to appear the same, but future research is needed to confirm these assumptions.

This study has only addressed tasks specific to automotive assembly. Caution is warranted when applying these results to scenarios that are different in nature from those tested. Before these scaling parameters can be applied to automotive stamping, power train, and especially non-automotive processes, further investigation of industry specific tasks is needed.

Lastly, these data suggest that differences seen in segment angles do not have a large effect on cumulative low back compression. Subject between the range of the 50F and 95M were found to yield similar results, which makes the methods outlined in this study appealing for researchers interested in developing a threshold limit value (TLV) for cumulative low back compression. Data are made available at 30 frames per second and can be collected in a lab setting with a defined set of scaling parameters. Given that the environment is virtual, injury data from current assembly plants could be collected and the processes deemed suitable to assess for low back loading could then be mocked up in the lab to represent the true life workstation layout. These data could identify the magnitude of loading observed for tasks that were associated with low back pain. Subsequently, this information could assist in defining a set of guidelines for exposure to cumulative loads.

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APPENDIX A

Full marker set with names of each marker based by body site

Scaling Study Marker Set			
1	Head Top	35	Right Rear Bicep
2	Head Left	36	Right Elbow
3	Head Right	37	Right Lateral Elbow
4	Head Left Back	38	Right Arm Left Lateral
5	Head Right Back	39	Right Arm Rear Lateral
6	Neck Base Rear	40	Wrist Mid Top Right
7	Mid-Clavicle	41	Metacarpal 2 Right
8	Left Acromion	42	Metacarpal 5 Right
9	Right Acromion	43	Thumb Base Right
10	Xiphoid	44	Left Thigh 1
11	Scapula	45	Left Thigh 2
12	Mid Back Left	46	Knee Lateral Left
13	Mid Back Right	47	Knee Front Left
14	Mid Back Center	48	Gastroc Left
15	Root	49	Lower Leg Lateral Left
16	Left ASIS	50	Lower Leg Rear Left
17	Right ASIS	51	Ankle Front Left
18	Left PSIS	52	Ankle Back Left
19	R PSIS	53	Toe Front Left
20	Right Upper Hip	54	Metatarsal 1 Left
21	Right Lower Hip	55	Metatarsal 5 Left
22	Left Upper Hip	56	Right Thigh 1
23	Left Lower Hip	57	Right Thigh 2
24	Left Front Bicep	58	Knee Lateral Right
25	Left Rear Bicep	59	Knee Front Right
26	Left Elbow	60	Gastroc Right
27	Left Lateral Elbow	61	Lower Leg Lateral Right
28	Lower Arm Left Lateral	62	Lower Leg Rear Right
29	Lower Arm Rear Lateral	63	Ankle Front Right
30	Wrist Mid Top Left	64	Ankle Back Right
31	Metacarpal 2 Left	65	Toe Front Right
32	Metacarpal 5 Left	66	Metatarsal 1 Right
33	Thumb Base Left	67	Metatarsal 5 Right
34	Right Front Bicep		

involvement. On your first day in the lab you will be scheduled to return 2 additional times. These times will be booked at your convenience.

POTENTIAL RISKS AND DISCOMFORTS

The physical risks associated with this study are minimal. You will be asked to perform tasks involving manual labour. However, these tasks have been chosen from the many jobs that are performed in the Pilot Plant on a daily basis, therefore you may even be familiar with the task. In order to ensure the activity is safe an ergonomic risk assessemnt has been completed on each of the three tasks. If, once the task has been described to you, you do not feel cabable of safely completing the activity, notify the researcher immediatley and you will not be required to perform that task.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Participating in this study will allow you to become involved in other departments of the workplace, namely the Work Center for Human Simulation and also to learn how research is performed and what the various stages of developing a vehicle include. You will also be contributing to the overall success of Ergonomic Analyses performed within this lab.

The results of this research will be published in a public journal which means that other researchers can learn about this study and have the opportunity to expand on the project, therfore adding to the knowledge about Ergonomics. When ergonomics is enhanced in the workplace, all employees benefit as the goal of this field is to reduce the risk of injury.

PAYMENT FOR PARTICIPATION

You will receive your regular hourly wade throughout your participation in this study; however you will not be paid in addition to this.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission.
The data collected during your particpation will be coded by number and thus your name will never be associated with this informtation. Individual results from the study will remain strictly confidential and will have no effect on your status within the workplace. Gross results will be made available to Ford Motor Company and to the scientific community but your personal data will be held in confidence.
All data will be stored in a locked lab in the Human Kinetics building at the University of Windsor. Only the researchers will have access to this data. Data will be kept for 2 years following the study, at which point all records and documents will be disposed.

Please note, data collected during this study may be used at a later date for further Ergonomic analyses. Your personal information will remain confidential at all times.

PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. If for any reason you wish to remove your data from the study, you have the right to do so.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE SUBJECTS

General study results will be posted on your employee bulletin board when they become available. At this time you will also see a notification indicating that individual results can be obtained by visiting the Work Center for Human Simulation. If you wish to receive individual feedback from the study but do not wish to visit the lab, you may contact the researcher directly, using the information provided on this form. Results will be mailed to you.

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. This study has been reviewed and received ethics clearance through the University of Windsor Research Ethics Board. If you have questions regarding your rights as a research subject, contact:

Research Ethics Coordinator
University of Windsor
Windsor, Ontario
N9B 3P4

Telephone: 519-253-3000, ext. 3916
E-mail: lbunn@uwindsor.ca

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study "Assessing the accuracy of ergonomic analyses when human anthropometry is scaled in a virtual environment" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

Name of Subject

Signature of Subject

Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

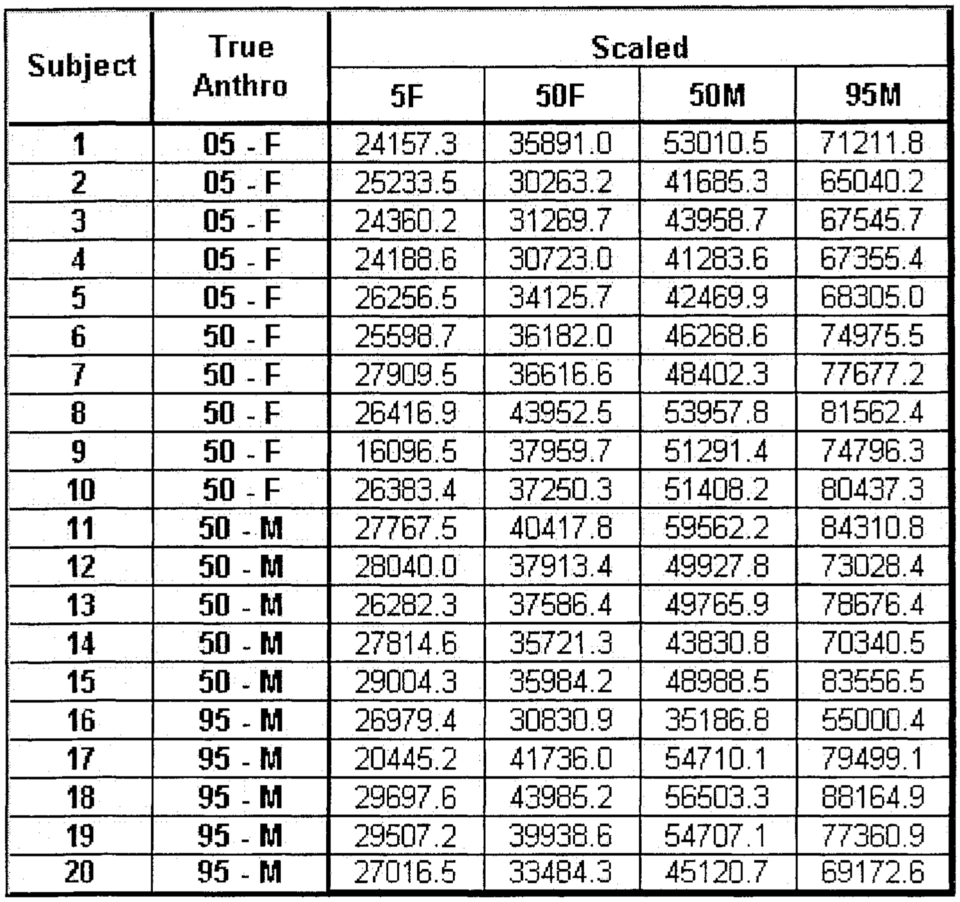
Signature of Investigator

Date

APPENDIX C

Subject Values for Cumulative Low Back Compression

The mean cumulative compression value (Ns) for each subject averaged across 3 trials for each of the 4 SA conditions. Cumulative compression was summed across all three tasks and the total duration was 30 seconds.



Subject	**True Anthro**	**Scaled**			
		5F	50F	50M	95M
1	**05 - F**	24157.3	35891.0	53010.5	71211.8
2	**05 - F**	25233.5	30263.2	41685.3	65040.2
3	**05 - F**	24360.2	31269.7	43958.7	67545.7
4	**05 - F**	24188.6	30723.0	41283.6	67355.4
5	**05 - F**	26256.5	34125.7	42469.9	68305.0
6	**50 - F**	25598.7	36182.0	46268.6	74975.5
7	**50 - F**	27909.5	36616.6	48402.3	77677.2
8	**50 - F**	26416.9	43952.5	53957.8	81562.4
9	**50 - F**	16096.5	37959.7	51291.4	74796.3
10	**50 - F**	26383.4	37250.3	51408.2	80437.3
11	**50 - M**	27767.5	40417.8	59562.2	84310.8
12	**50 - M**	28040.0	37913.4	49927.8	73028.4
13	**50 - M**	26282.3	37586.4	49765.9	78676.4
14	**50 - M**	27814.6	35721.3	43830.8	70340.5
15	**50 - M**	29004.3	35984.2	48988.5	83556.5
16	**95 - M**	26979.4	30830.9	35186.8	55000.4
17	**95 - M**	20445.2	41736.0	54710.1	79499.1
18	**95 - M**	29697.6	43985.2	56503.3	88164.9
19	**95 - M**	29507.2	39938.6	54707.1	77360.9
20	**95 - M**	27016.5	33484.3	45120.7	69172.6

APPENDIX D

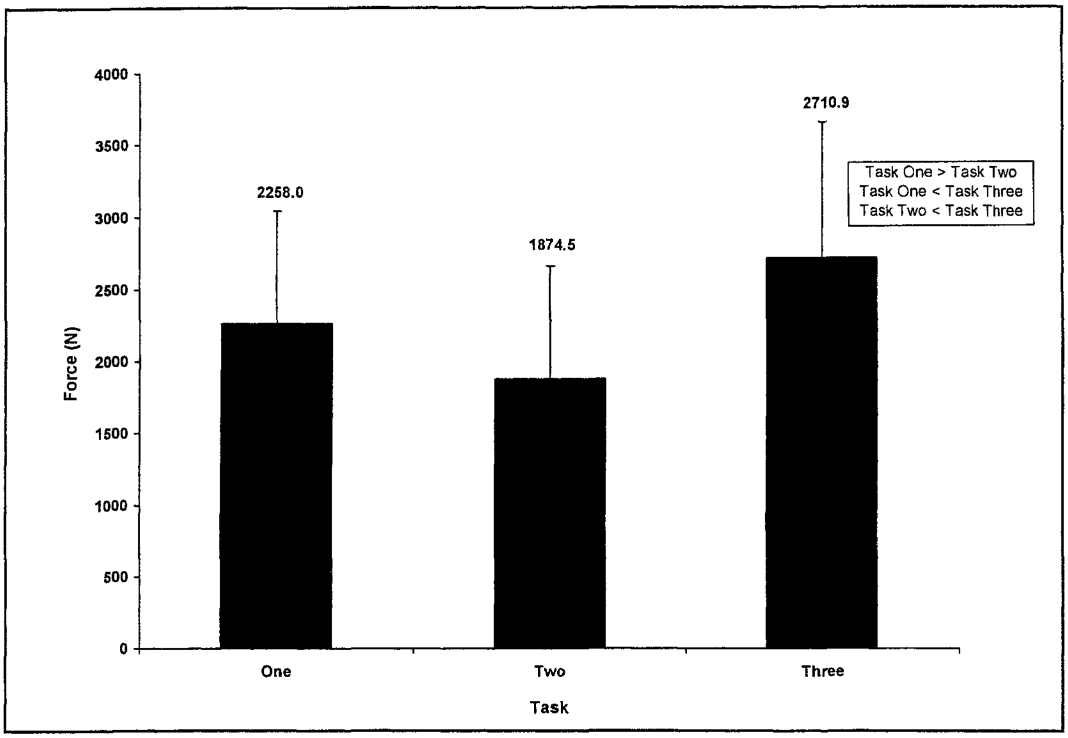
Subject Values for Peak Low Back Compression

The peak compressive force (Newtons) for each task is presented below. Data is averaged across 3 trials for each of the 20 subjects.

Subject	True Anthro	Scaled Anthropometry											
		5F			50F			50M			95M		
		Task 1	Task 2	Task 3	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3	Task 1	Task 2	Task 3
1	05 - F	1159.2	1086.9	1720.5	1668.6	1599.0	2419.8	2332.2	2386.9	3326.8	3051.1	3118.5	4516.0
2	05 - F	1314.4	878.5	1788.6	1694.7	873.4	2083.1	2429.7	1381.8	3089.9	3184.1	2030.4	4016.4
3	05 - F	1403.1	931.9	1816.7	1810.6	965.3	2086.1	2390.6	1689.1	2741.0	3315.7	2659.3	3800.6
4	05 - F	1233.8	814.7	1436.1	1665.5	1083.3	1370.8	2582.9	1655.1	2030.7	3293.1	2209.8	3090.3
5	05 - F	1482.1	943.4	2123.5	1941.6	1204.0	2194.3	2677.3	2256.1	2215.1	3599.4	3307.3	3823.8
6	50 - F	1305.2	1110.5	1886.7	1655.6	1498.6	2393.5	2376.3	2353.5	2952.3	3544.1	2727.9	3877.8
7	50 - F	1327.3	992.3	1993.4	2044.9	1388.0	1448.3	2741.4	1998.3	2383.8	3594.7	3252.8	2888.0
8	50 - F	1437.2	1034.4	2006.1	1915.9	1777.6	2215.7	2546.4	2335.5	2827.8	3514.1	3260.4	4055.7
9	50 - F	1226.9	1113.7	1898.7	1655.9	1506.7	2144.7	2482.3	2096.9	2928.7	3356.9	2772.1	3978.2
10	50 - F	1376.2	1284.6	1451.7	1800.1	1351.4	2189.6	2426.0	1898.0	3222.7	3325.0	2893.9	4501.1
11	50 - M	1327.6	1215.4	1860.3	1877.4	1624.1	2609.5	2563.9	2562.3	3884.7	3330.8	3329.4	5265.2
12	50 - M	1369.6	1147.1	2197.0	1773.8	1558.4	2326.0	2391.1	2004.6	2948.9	3033.9	2923.0	3997.1
13	50 - M	1339.1	1143.4	1865.8	1651.5	1474.3	2562.0	2560.1	2071.8	2940.2	3353.3	2983.8	4370.6
14	50 - M	1322.4	1137.3	2069.9	1751.8	1598.7	2114.9	2264.0	1997.5	3027.1	3285.2	3353.2	3905.3
15	50 - M	1350.3	953.2	1662.6	1933.4	1163.0	1454.2	2697.7	1874.5	2187.8	3459.0	3238.1	3838.8
16	95 - M	1349.9	1021.7	1907.4	1775.9	1294.2	1625.7	2384.5	1696.6	1919.8	3274.4	2832.2	2101.0
17	95 - M	1323.1	1172.3	1887.6	1918.6	1755.8	2267.1	2718.3	2422.8	3127.2	3378.9	3338.9	4344.8
18	95 - M	1515.7	1333.0	1891.1	1897.4	1813.5	2596.7	2566.2	2485.7	3610.2	3453.6	3735.4	4862.7
19	95 - M	1453.7	1073.3	1807.8	1799.6	1476.1	2875.2	2957.1	2081.2	3777.0	3820.3	2828.4	4167.9
20	95 - M	1302.3	913.4	1709.6	1611.8	1220.1	2076.2	2556.8	1736.2	3022.1	3067.4	2650.7	3275.2

APPENDIX E

Main effect of Task for peak low back compression



The main effect of Task for peak low back compression has been shown ($p<0.0001$). Standard deviation bars are shown ($n=80$).

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