Effects of Shoulder, Low Back, or Knee Strength Degradation on Motion Control Strategies and Injury Risk during Manual Materials Handling

Sponsor: National Institute for Occupational Safety and Health

Grant #: K01OH007838

September 1, 2003 to December 31, 2007

Xudong Zhang*, Ph.D. (Principal Investigator)
Daniel Bartlett, M.S. (Graduate Assistant)
Kang Li, M.S. (Graduate Assistant)
Raziel Riemer, M.S. (Graduate Assistant)

Biomechanics and Ergonomics Laboratory
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign
1206 West Green Street
Urbana, IL 61801

March 2008

*Current address for correspondence: Orthopaedic Research Laboratories, University of Pittsburgh, 3820 South Water Street, Pittsburgh, PA 15203. Tel: 412-586-3940; fax: 412-586-3979.

Table of Contents

List of Figures

List of Tables

Abstract

The general objective of this research supported by a NIOSH K01 grant is to systematically investigate whether and how dynamic (isokinetic) muscular strengths in three major body joints (the shoulder, low back, and knee) affect the strategies in and injury risk associated with the performance of manual materials-handling. Our long-term goal is to develop quantitative tools and guidelines that integrate the measurable strength and movement information for the recognition, prediction, and prevention of occupational musculoskeletal injuries. In this study, we first evaluated the dynamic (isokinetic) strengths of human subjects, and established a sizable dynamic strength databases with various stratification schemes; we designed and conducted a unique simulated manual materials-handling experiment to investigate subjects' batch-assorting strategy and lifting kinematics under various task conditions created by varying load-handled, body symmetry, and knowledge of strength. We identified a relationship between dynamic isokinetic strength and the batch-assorting strategy to initiate a manual materials-handling task and an effect of self-knowledge of the strength on that relationship. We also discovered that relative strength between the back and knees can differentiate and predict lifting biomechanics: persons with back strength greater than their total knee strength tended to use a back lift strategy, and vice versa. We did not find any significant difference in dynamic strength between asymptomatic individuals and self-claimed symptomatic individuals with select joint (shoulder, back, or knee) pain. The results of this study rendered important practical implications on the utility of isokinetic strength tests in worker selection or screening, on how job training and design should be conducted to better prevent injuries incurred during manual materials-handling, and on incorporation of strength factor in digital human modeling (DHM) technology for ergonomics and design.

Highlights/Significant Findings

This Career Development Award (K01) grant created a tremendous momentum at a very critical time in the Principal Investigator's career. With such a momentum, the PI steadfastly established a research program dedicated to occupational biomechanics and injury prevention. As a developing investigator, he subsequently received noteworthy recognitions including a University of Illinois college of engineering faculty research award (Xerox Award), and invitations to the editorial board of Human Factors and to the US delegation of NSF-sponsored US-China Biomechanics Workshops.

The overall goal of this study was to elucidate the complex and long debated relationship between muscular strength and risk of injury associated with manual materials-handling. We believe this was the first study ever that identified the relationships between the muscular strengths in three major body joints (the shoulder, back, and knee) and manual materials-handling strategies examined from both decision making (the batch-assorting strategy to initiate a task) and biomechanical (lifting mechanics) perspectives.

There were three significant major findings. First, we identified a relationship between dynamic isokinetic strength and the batch-assorting strategy to initiate a manual materials-handling task and an effect of self-knowledge of the strength on that relationship. This batch-assorting strategy embodies the decision of balancing load and pace in manual materials-handling. We found that stronger persons tended to adopt a strategy corresponding to heavier load per carry and fewer carries per batch, and that those who received the knowledge of their strengths became more emboldened in load handling. Second, we discovered that relative strength between the back and knees can differentiate and predict lifting biomechanics: persons with back strength greater than their total knee strength tended to use a back lift strategy, and vice versa. Third, in establishing dynamic isokinetic strength databases for our study, we concluded that there was no significant difference in dynamic strength between asymptomatic individuals and self-claimed symptomatic individuals with select joint (shoulder, back, or knee) pain.

Translation of Findings

Collectively, the research findings from this study translate into several important practical implications on occupational health and injury prevention. One is on the utility of isokinetic strength tests in worker selection or screening. In a review of research on isokinetic testing, Newton and Waddell (1993) concluded that there is insufficient evidence indicating isokinetic testing is appropriate for pre-employment screening or clinical assessments. This study, however, has lent some support to the use of isokinetic strength testing in differentiating individuals' abilities and preferred strategies in the performance of a manual materials-handling task. This is in opposition to the assertion that in order for a physical aptitude test to be valid it must utilize the same muscle groups in the manner they would be emphasized in performing the actual work task (Dunn & Dawson, 1994). The findings from the current study indicate that tests of dynamic (isokinetic) joint strengths may be useful for identifying individuals who are likely to exert themselves at higher levels and who are likely to use a distinct lifting technique (i.e., back lift or leg lift) of particular biomechanical consequence. This is a critical initial step toward gaining a clearer understanding of an important but tantalizing (and so far contentious) issue in occupational health and ergonomics; that is, whether individuals with greater strengths are at greater risk of occupational injury? Although a clear answer to this questions will com

Another implication pertains to how job training and design should be conducted to better prevent injuries incurred during manual materials-handling. A handling strategy of heavier load per carry and fewer carries per batch translates into adverse biomechanical consequences (e.g., increased joint loading and low-back stress, and decreased margin of safety). Such a strategy adopted by stronger individuals seems to reflect a "risk homeostasis" model (Wilde, 1998) of coping with injury risk associated manual acts. Physical training including muscular strength training has been advocated as a tool for increasing work tolerance (Genaidy, Karwowksi, Guo, Hidalgo, & Garbutt, 1992). The benefit of such training, without intervention, may be offset by increased average load magnitude in handling as evidenced in the current study. Explicit instruction or "designing-out" risky options would be necessary intervention means, particularly for repetitive handling tasks such as palletizing. In addition, provision of information about people's physical capacity intended to help adopting a more contained or cautious strategy, if not furnished properly, may have an opposite effect. While absolute performance scores may not be meaningful, relative ordinal data as provided in the current study could lead to a more risk-taking response. In addition, when lifting techniques are prescribed or taught, or strength training is provided, the strength profiles of the trainees should be carefully assessed and taken into account to maximize the efficacy of the programs.

The third implication is on the development of digital human modeling (DHM) technology—a technology that is transforming ergonomics work and workplace design. Most commercial DHM software tools create manikins or digital human "avatars" and simulated physical actions (such as a manual materials-handling act). Many physical or cognitive attributes are not included as the input variables for simulating physical actions in these tools, among which muscular strength is an important factor. It is well accepted that strength is posture- or movement-dependent (Chaffin, Andersson, & Martin, 1999). It is also intuitive that strength may be indicative of the movement performance at or near the maximal level (e.g., the maximum acceleration producible). It was however not well understood whether strength could ever influence performance in which only sub-maximal, moderate exertions are needed. The findings from the current study suggest that the strength factor may affect both the high-level decision making (e.g., what effort level to choose) and the low-level motor control (e.g., which body segment as the prime mover) during goal-driven (as opposed to passive) physical performance (Li & Zhang, 2007). It therefore will be crucial for the next generation DHM tools to incorporate the strength information so that they can render more realistic simulation of works in work places and predict associated ergonomic risk more accurately.

Outcomes/Relevance/Impact

The present study has provided new knowledge and clearer understanding of the relation between dynamic strength and manual materials-handling strategies. The knowledge, understanding, and their implication can potentially have long impacts on ergonomic design and occupational injury prevention. The study demonstrates the applicability of isokinetic strength tests for predicting manual materials-handling behavior in balancing productivity and injury prevention. It adds evidence supporting the use of dynamic strength testing for worker selection in general. The clearer understanding of the strength guards the benefits of strength training, and necessitates explicit instruction or "designing-out" risky options for controlling the tendency of choosing heavier load or a lifting style to begin a manual materials-handling job. The effect of strength knowledge has implications on how to design information about mechanical capacity presented to workers to facilitate a more contained or cautious manual materials-handling strategy. The identified and quantified effects of dynamic strength on both the decision making and biomechanics during a manual materials-handling task will lead to renovations in development of digital human modeling and ergonomic design tools.

Scientific Report

Background

Despite advancement in the automation of materials handling, many tasks today still must be carried out manually. Overexertions during manual materials-handling tasks in the workplace can significantly elevate the risk of musculoskeletal disorders or injuries. According to the Bureau of Labor Statistics, in 2002 more than 200,000 injuries resulted from overexertion while lifting, and nearly 60,000 others were due to overexertion in holding, carrying, or turning objects (Bureau of Labor Statistics, n.d.). Manual materials-handling tasks vary widely, as do individuals' physical capacities. Because of this dual variability in the demand-capacity match, accounting for the variables that constitute a manual materials-handling task and investigating their effects on performance is important (Chaffin et al., 1999).

Muscle strengths can also change due to reasons including aging, impairment, or injury. The changes can significantly impact the lives for a large yet increasing portion of our population. For instance, low back pain, as one of the most prevalent and costly musculoskeletal disorders among industrial workers—estimated annual cost has been as high as $100 billions (Marras, 2000)—is usually accompanied with back strength degradation (Chaffin, 1974; Kishino et al., 1985; Langrana, Lee, Alexander, & Mayott, 1984). Leg or back muscle strength for the steadily expanding elderly population could, on average, decline by 20% to 50% or more (Balogun, Olawoye, & Oladipo, 1991; Murray, Duthie, Gambert, Sepic, & Mollinger, 1985; Murray, Gardner, Mollinger, & Sepic, 1980; Vandervoort, Hayes, & Belanger, 1986; Vandervoort, Kramer, & Wharram, 1990; Young, Stokes, & Crowe, 1984, 1985). Comparable age-related asymptomatic shoulder strength degeneration has also been documented (Andrews, Thomas, & Bohannon, 1996; Hughes, Johnson, O'Driscoll, & An, 1999a, 1999b; Rice, Cunningham, Paterson, & Rechnitzer, 1989).

The difference of muscular strength may influence functional capabilities and possibly impact the risk of injury or re-injury in performing physical activities. This latter consequence has been demonstrated most notably in studies relating muscle weakness to the balance control or recovery abilities, and the risk of fall (Kuo & Zajac, 1993; Smeesters, Hayes, & McMahon, 2001; Whipple, 1987; Wojcik, Thelen, Schultz, Ashton-Miller, & Alexander, 1999). In the balance maintenance and recovery research paradigm, although age differences have been evidenced in empirical investigations (Thelen, Wojcik, Schultz, Ashton-Miller, & Alexander, 1997; Wojcik et al., 1999), a challenge persists in elucidating whether the difference is attributable to strength weakness, sensory degeneration, or reduced capability of rapid torque development (not necessarily correlated with strength). The difficulty of relating the voluntary strength measures to an involuntary act was reflected in the study by Smeesters et al., (2001), which identified only a modest correlation between the lower extremity strength and the ability to recover a trip.

Under occupational settings, while longitudinal studies (e.g., Cady, Bischoff, O'Connell, Thomas, & Allan, 1979; Chaffin, Herrin, & Keyserling, 1978; Chaffin & Park, 1973) have indirectly suggested that greater strength may be associated with reduced propensity for injury, there is no direct convincing evidence to support that strength degradation increases the risk of injury or re-injury (Mandell et al., 1993; Newton & Waddell, 1993). The validity or value of strength testing in patient treatment and evaluation continues to receive scientific debates (Mooney & Andersson, 1994). In sum, for tasks that are more volitional and job demands more controllable, whether individuals with relatively weaker or degraded muscular strength are at higher or increased risk awaits further investigation. This research void is long well recognized as a gap in our knowledge regarding the relationship between muscular strength and prediction of future injury (Chaffin et al., 1999).

Manual materials-handling is a common occupational task that can be significantly affected by muscular strength, and it presents a major health and safety risk in industry. In fact, according to a survey by the National Longitudinal Surveys of Labor Market Experience, the inability to lift or carry weights was singled out as the factor most significantly related to limitations in the kind or amount of work performed by the elderly

(Chirikos & Nestel, 1985). Another survey of 5,100 men and 4,705 women aged 55-74 years by Kovar and LaCroix (1987) indicated that up to 17% reported the inability and another 41% reported difficulty when tasks including stooping, crouching, lifting and carrying a 25-lbs weight were being performed. It is for these reasons that considerable investigative efforts have been dedicated to quantifying the relationship between muscular strength and manual materials-handling capacity (Chaffin et al., 1978; Garg, Mital, & Asfour, 1980; Poulsen, 1981; Pytel & Kamon, 1981; Wilmarth & Herekar, 1991).

However, manual materials-handling is often not performed at someone's short-term physical capacity, and the effects of the muscular strength on the performance and associated injury risk are highly complex, particularly when there are alternatives to complete a task, allowing different strategies, self-protective or otherwise, to be adopted. Under such circumstances, a multitude of factors can influence people's decision making and selection of strategies or actions. For instance, it is recommended that workers verify the heaviness of a load before handling in order to reduce the risk of injury (Genaidy et al., 1998), but the process of which is under the influence of a variety of task factors (see Karwowski et al., 1999 for a discussion of these factors). In Ciriello and Snook (1983), it was observed that several factors can affect the weights perceived to be acceptable, including distance, height, and frequency along with the size of the object to be lifted. Karwowski and Yates (1986) corroborated that the perception of ability when lifting self-selected loads is influenced by the frequency of the lift. Nicholson and Legg (1986) allowed young men to vary their lifting load and pace in determining a maximum acceptable workload; they concurred that the pace and load had effects, but they concluded that the maximum acceptable workload is affected primarily by factors that are not physiological. Additional studies have also examined the effects of non-task-related or personal variables on individuals' perceptions about their lifting abilities. Jackson and Sekula (1999) reported that, given strength-matched groups of men and women, the women perceived lifting the same load as more difficult. Further, Brownsword (1987) found that some individuals' personalities could compel them to perform tasks at a level corresponding to the perceived competition from individuals around them. It has also been demonstrated that the experience one possesses may influence the amount of weight which they choose to lift (Mital, 1987). Bandura (1986) stated that extrinsic feedback would affect the way individuals carry out tasks, and might especially influence competency judgments in unfamiliar tasks. Ryan, Greguras, and Ployhart (1996) found that if a physical aptitude test is not closely related to the actual task, then participation may be affected due to individuals' judgments of the test as a fair evaluative measure.

To date, there has been study that carefully documented dynamic strength of major body joints, and investigated the relationships between the muscular strengths and manual materials-handling strategies examined from both decision making (the batch-assorting strategy to initiate a task) and biomechanical (lifting mechanics) perspectives.

Specific Aims

The **general objective** of this research is to systematically investigate whether and how dynamic (isokinetic) muscular strengths in three major body joints (the shoulder, low back, and knee) affect the strategies in and injury risk associated with the performance of manual materials-handling. Our **long-term goal** is to develop quantitative tools and guidelines that integrate the measurable strength and movement information for the recognition, prediction, and prevention of occupational musculoskeletal injuries. This initial research project seeks to achieve the following **specific aims**:

1. To evaluate the dynamic (isokinetic) strengths of human subjects, and through analysis of acquired strength profiles, to establish strength databases with different schemes of stratifying subject groups for comparative studies: asymptomatic vs. symptomatic, stronger vs. weaker and with vs. without self-knowledge of strengths.

   Hypothesis (H1): The dynamic joint strengths of asymptomatic subjects are significantly different from those of symptomatic subjects.

2. To design and conduct simulated manual materials-handling experiments to measure subjects' batch-assorting strategy and lifting kinematics under various task conditions created by varying load-handled, body symmetry, and knowledge of strength.

3. To investigate the relation between dynamic (isokinetic) strength and batch-assorting strategy to initiate manual materials-handling, and the effect of self-knowledge of the strengths on that relation.

   Hypothesis (H2): Stronger and weaker individuals use different batch-assorting strategy, and self-knowledge of the strength significantly affects the strategy.

4. To investigate the relation between back-knee strength ratio and lifting mechanics during manual materials-handling, and the effects of task factors on that relation.

   Hypothesis (H3): Individuals with stronger back strength (relative to the total knee strengths) tend to use a back-lift strategy and verse vice, and these tendencies can be affected by task factors.

Procedures

Subjects

A total of 64 subjects were recruited to participate in the study, and were classified into two groups: a healthy asymptomatic group of 45 subjects (25 males and 20 females), and a self-claimed symptomatic group of 19 subjects (10 males and 9 females). The healthy asymptomatic subjects were recruited from the university community while and the self-claimed symptomatic subjects were recruited through contact and advertisement (see Appendix A) at Departments of Occupational Medicine and Physical and Rehabilitation Medicine of Carle Clinic (Urbana, IL). The mean weights (±SD) of the asymoptomatic subjects were 79.12 (±14.10) and 61.64 (±10.41) kg for men and women, respectively; the mean heights were 180.23(±7.64) cm for the men and 165.22(±7.16) cm for the women. Their age ranged from 20 to 41 (average 24.28±5.36). The mean weights (±SD) of the symoptomatic subjects were 88.74 (±22.81) and 68.52 (±15.86) kg for men and women, respectively; the mean heights were 177.49 (±7.61) cm for the men and 165.59 (±4.92) cm for the women. All subjects provided informed consent (Appendix B) and completed a questionnaire (Appendix C) before proceeding to the experiments.

Strength Testing Experiment

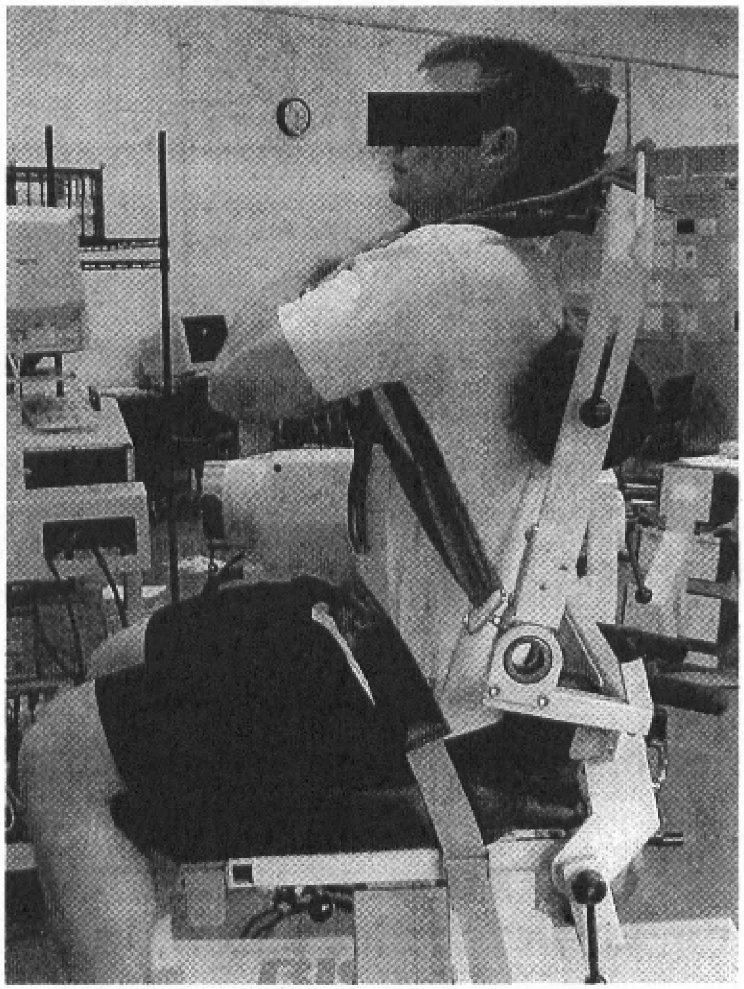


Figure 1. A participant secured into the trunk extension/flexion attachment utilized in the testing of isokinetic back extension strength.

The first experiment involved testing the participants' dynamic (isokinetic) strengths on a Biodex System 2 dynamometer (Biodex Medical Systems; Shirley, NY). Seven joint strengths were tested: back (trunk) extension, right and left knee extensions, and right and left shoulder extensions and abductions. The joint rotation speed was controlled at 60° per second for all the tests. The back extension was completed first, followed by the knee extensions, and then by shoulder extensions and abductions. Dominant limbs were tested first in the bilateral tests, and participants performed sub-maximal warm-ups before the tests. Each test entailed completing three sets of five repetitions for each joint-direction.

Participants were provided with a rest period of approximately 90 seconds between sets to minimize fatigue effect, according to the findings of Parcell, Sawyer, Tricoli, and Chinevere (2002). Figure 1 shows a participant at the beginning of a back extension test. The range of motion settings for the tests were as follows: 100° to 150° for back extension, 0° to 90° for knee extension, and 0° to 90° for shoulder extension. The lower limit of the range of shoulder abduction varied by individual (generally between 9° and 22°) due to potential interference from the seat of the Biodex unit. Narrower shoulders, therefore, produced greater minimum angles than wider shoulders; the upper limit of the range was 90°.

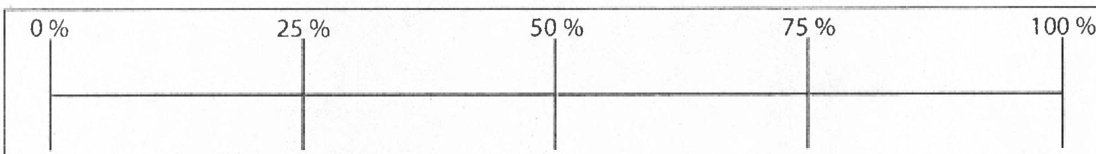
Manual Materials-Handing Experiment

The manual materials-handling experiment was conducted on a different day after a participant completed the strength test and was selected to participate based on a preliminary analysis of his or her strength data. As most of the self-claimed symptomatic subjects were able to continue with the experiment and we found no difference in the strengths between the two groups, only asymptomatic subjects were involved in this experiment. Among the asymptomatic subject group, 32 subjects, 16 men and 16 women, participated in the manual materials-handling experiment and were able to complete all the tasks. The mean weights and heights (± standard deviation) of the men and women were 79.52 (±15.62) kg and 181.61 (±8.85) cm, and 61.80 (±11.35) kg and 165.26 (±7.33) cm, respectively. Participants ranged in age from 20 to 41 (average 24.28±5.36).

Maximum torque values from each joint-direction test were obtained and summed over the seven joint-directions to generate a total isokinetic strength (TIS) value. The 32 subjects were selected to fit into two subgroups of sixteen, with each subgroup composed of eight men and eight women. Participants were sorted such that the strength differences between the two groups were minimized. The differences in TIS values between the two subgroups were statistically insignificant according to a *t*-test ($p = .898$); the differences in mean strength values for individual joints were also found to be insignificant (*p*-values ranged from .429 to .979).

Table 1. An example of the table presenting strength testing results to the feedback group.

Strength Test	Results		
	Max Torque (Nm)	Percentile	
		Within Gender	Within All Participants
Back Extension	267	53	71
Shoulder Abduction (L)	47	27	61
Shoulder Abduction (R)	49	20	58
Shoulder Extension (L)	56	33	68
Shoulder Extension (R)	62	33	68
Knee Extension (L)	130	27	48
Knee Extension (R)	132	13	42
Total Isokinetic Strength	743	20	48



Please indicate on the scale above (make a mark) and on the line below (a numeric value) where you believe that your overall strength capabilities lie on the continuum above (i.e. 50% - better than 50% of people)

__________%

Figure 2. The scale upon which participants indicated their prediction of their over-all strength relative to the general population.

The participants were asked to estimate their overall strengths relative to the general population by placing a mark on a graduated scale (see Figure 2). Following that, the participants in one subgroup were given feedback on their strengths relative to other participants in this study—this subgroup will be named "Feedback Group" hereafter. This feedback included strength scores (torque values), percentiles within their gender, and percentiles among all participants for the seven individual joint maximum torques as well as the TIS values recorded in the first session (see Table 1). The feedback was presented using the same graduate scale (Figure 2) along with verbal explanations by an experimenter to each participant individually. The participants in another subgroup were not provided with any feedback concerning their strength testing results—this subgroup will be named "No-Feedback Group" hereafter. Both subgroups subsequently performed the same manual materials-handling task.

The manual materials-handling task required participants to transfer batches of plates in a crate whose dimensions are 36 cm (W) by 38 cm (D) by 28 cm (H). Plates were identical and weighed 5 lbs (2.27 kg) each. Participants were not informed of the weight of the plates. They each completed twelve trials—6 batches consisting of one through six plates and two replications—in a completely randomized order and at a self-preferred pace. Participants were allowed to assort a batch of more than one plate into any combination. For example, for a batch of three plates, a participant may choose to transfer all three in one carry, two in one carry and one in the other, or one in each of three carries. The number of plates transferred in each carry was recorded. Participants were allowed to rest at any time between carries, and were reminded after every third batch that they may rest.

The manual materials-handling task consisted of the following sequence of steps:

1. Participants began standing with feet spread to approximately hip width facing the crate at position 1 (see Appendix D for a depiction of the experimental setup).
2. Participants picked the crate up off of the floor, stand up, and holding the crate at about naval height, carried it to the shelving unit (position 2).

3. They set the crate down on the lower shelf of the unit, and allowed it to rest there momentarily without letting go of the crate.
4. Participants then lifted the crate off of the shelf, turned 90° to the left, and set the crate on the floor (position 3).
5. They allowed the crate to rest on the floor momentarily while not letting go of the crate, then lifted the crate from the floor, returned to an upright position, and paused momentarily while holding both arms at an angle approximately parallel with the floor.
6. Participants turned back to the right 90° and set the crate upon the lower shelf once again (position 4).
7. They allowed the crate to rest there momentarily without letting go of the crate and then lifted it off of the shelf once again.
8. Taking a step back with one foot, participants elevated the crate to the level of the upper shelf, and set the crate on the top shelf while bringing the aforementioned foot back forward.
9. They allowed the crate to rest on the upper shelf momentarily (position 5), lifted it from the shelf, took a step back with one foot, and lowered the crate to naval height again.
10. Participants then set the crate on the lower shelf once again (position 6) while bringing the displaced foot back forward.

Methodology

In order to test our first hypothesis (H1) and compare the strengths between asymptomatic and symptomatic subjects, five individual analyses of variance (ANOVAs) were conducted to examine the effects of gender, subject type (asymptomatic vs. symptomatic) and their interaction on the five isokinetic strength measures (i.e., back extension, shoulder abduction, shoulder extension, knee extension and total isokinetic strength). A Multivariate Analysis of Variance (MANOVA) using a Pillai's Trace criterion was also conducted to ensure the effects exist since multiple dependents were involved in the analysis and the sample sizes were unequal. All these analyses were carried out using the General Linear Models procedures of SAS (SAS Institute, Cary, NC) software program.

The subsequent analysis only involved the 32 asymptomatic subjects that completed the manual materials-handling experiment in order to test the second and third hypotheses. The strength data were analyzed for comparisons between various groups and with previously published dynamic strength data. The correlations of joint strengths were also inspected. Differences between participants' own estimated strengths in terms of percentile ranks relative to the general population and the actual percentile ranks were examined. Two measures, the average number of carries per batch of *n* plates (ACB_n) and the average load per carry (ALC) across the batches of 4, 5, and 6 weights were defined in order to quantify the material handling strategies adopted by the participants. Due to the discontinuous nature of ACB_n and ALC, a logistic regression was performed (Stokes, Davis, & Koch., 1995) to analyze the association of TIS with ACB_n and with ALC, and the effect of knowledge feedback. A term was included in the logistic regression model to examine the interaction of TIS and gender. Note that since there was little variation in ACB_n and ALC for batches of one, two, and three plates, they were omitted from the analysis.

The measurement of manual material-handling movements required reflective spherical markers to be placed on subjects' surface bony landmarks (see Figure 3) identifying body joints including the wrists, elbows, shoulders, hips (greater trochanters), knees, and ankles, and sacrum/pelvis prominences including the anterior superior iliac spines (ASIS), the posterior superior iliac spines (PSIS), and spinous processes (C7, L5, S1). The three-dimensional (3D) coordinates of the markers during the entire manual materials-handling task were captured by a five-camera Vicon 250 system (Oxford Metrics, UK) at a sampling frequency of 120 Hz. The data were tracked, labeled, properly truncated, and then organized according to the experimental design.

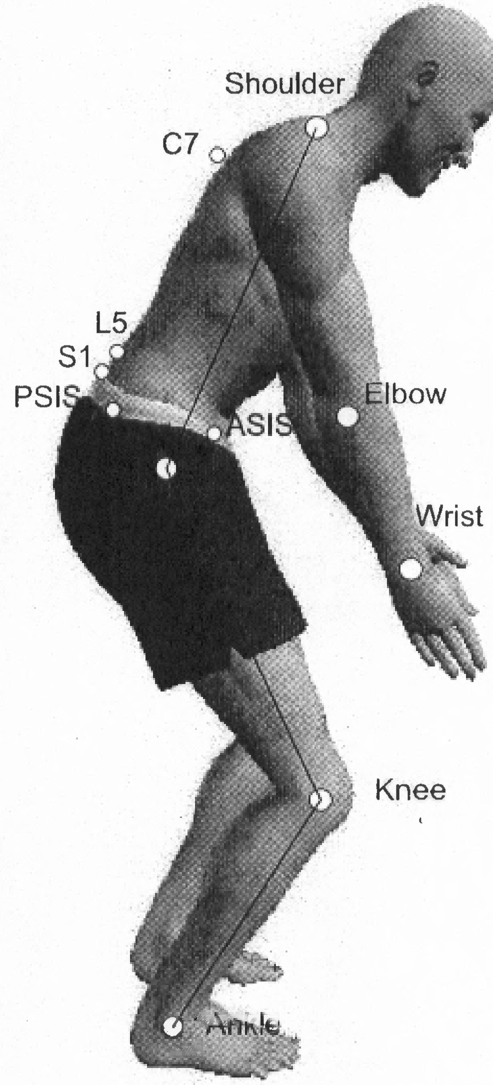


Figure 3. Reflective marker placement designed to capture the lifting kinematics.

The acquired 3D coordinates of markers on shoulders, hips, knees, and ankles during the lifting acts were projected onto the mid-sagittal plane and converted into two-dimensional (2D) data. The lumbar vertebral angle, knee angle and ankle angle were then derived from these 2D marker coordinate data, and served as input to estimate the postural index (Burgess-Limerick & Abernethy, 1997). The resulting postural index was then used as the dependent variable in subsequent statistical analyses. The preceding data analyses were carried out using MATLAB® programs (The MathWorks, Boston, MA). Note that in this study, the lumbar vertebral angle was defined by the angle created by the C7, ASIS and PSIS markers as opposed to the angle in Burgess-Limerick and Abernethy (1997), which was constructed by T1, ASIS and PSIS markers with the assumption that the slight relative motion between T1 and C7 does not affect the lumbar vertebral angle.

In order to examine the effect of muscle strength on lifting strategy, the participants were further divided into another two subgroups, back-stronger subgroup and knee-stronger subgroup, depending on whether their back strength was greater or less than their total knee strength (summation of the strengths of both knees). According to the above classification criteria, 19 subjects belong to the knee-stronger subgroup and the rest 13 subjects belong to the back-stronger subgroup. An unbalanced analysis of variance (ANOVA) was then conducted to examine the effect of gender, load magnitude, knowledge feedback, and relative stronger joint on lifting strategy, again using the General Linear Models procedures of SAS (SAS Institute, Cary, NC) software program. Note that since not all participants carried more than three weights during each task, only three weight levels (2.27 kg, 5.54kg, and 6.87kg) were included in the analysis, i.e., 367 out of 486, the total number of carries (lifting trials), were included in the analysis. Since participants were allowed to assort a batch of more than one plate into any combination, the carries for each weight level across subject are varied, ranging from two to sixteen, the mean lifting index of each weight level for each subject (32*3=96 observations) was used as the observation in the analysis.

To visualize the lifting strategy in a 2D strength map formed by the acquired back and total knee strength measures, the lifting strategy was classified into three classes according to the following criterion: a lifting index larger than 0.5 represents a leg lift and a lifting index smaller than 0.38 represents a back lift otherwise a mixed lift occurs (Figure 4). The critical values, 0.38 and 0.5, were determined as follows. The mean lifting index of each subject and the difference between the total knee and back strengths (i.e., total knee strength - back strength) were first normalized and then classified into 2 classes using a K-means clustering method (Heijden, Duin, Ridder, & Tax, 2004). The boundaries of the overlapped region of the two classes in terms of lifting index were used as the critical values (Figure 4).

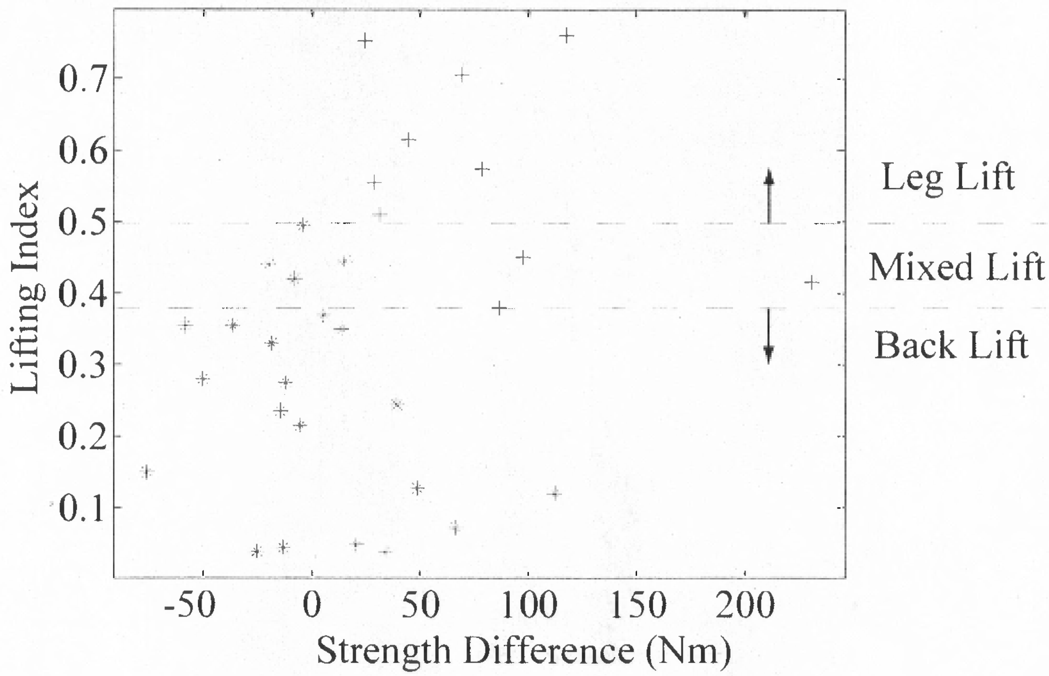


Figure 4. Normalized lifting index and strength difference were classified to two classes (* vs. +) by the K-means clustering method. The dash lines represent the boundaries as well as the critical values.

Results and Discussion

The dynamic (isokinetic) joint strengths of asymptomatic subjects are not significantly different from those of symptomatic subjects considered in this study (Table 2). Both the MANOVA and the individual ANOVA's showed that the main effect of subject type and the interaction between subject type and gender on any of the strength measures were not significant. Expectedly, the gender factor had significantly effects on all the strengths (Pillai's Trace=0.65, $F(4,57)=26.62$, $P<0.0001$). These results suggested that the two groups (asymptomatic vs. symptomatic) had no difference in all the strengths. Therefore, we rejected the first hypothesis (H1). The minimum and maximum TIS scores recorded were 247 and 1367 Nm, respectively. The TIS values formed a normal distribution according to a Shapiro-Wilkes test for normality (p = .5571).

Overall, subjects in this study had lower strength scores in most tests compared to isokinetic strength data available in literature (Dvir, 2004; Perrin, 1993). A statistical summary of the individual joint isokinetic strengths and total isokinetic strength is presented in Table 2, and Table 3 compares the strength values recorded here to those presented in Dvir (2004) and Perrin (1993).

Table 2. Mean (±SD) values of back, knee, and shoulder extension, shoulder abduction, and total isokinetic strengths for men vs. women, asymptomatic vs. symptomatic subjects, and all participants combined.

	Joint Strengths (Nm)				
Gender	Back Extension	Shoulder Abduction *	Shoulder Extension *	Knee Extension *	TIS
Men(n=35)	292 ± 77	58 ± 14	66 ± 14	163 ± 43	866 ± 194
Women(n=29)	190 ± 56	31 ± 8	33 ± 7	106 ± 39	532 ± 152
Subject type	Back Extension	Shoulder Abduction *	Shoulder Extension *	Knee Extension *	TIS
Asymptomatic (n=45)	255 ± 80	48 ± 17	53 ± 19	138 ± 47	730 ± 226
Symptomatic (n=19)	225 ± 94	43 ± 21	49 ± 23	136± 58	678 ± 280
Both	246 ± 85	46 ± 18	51 ± 20	137 ± 50	715± 242

* Left and right sides averaged

Table 3. Isokinetic strengths of individuals free from physical malady reported in two reviews of testing data versus the strengths reported in this study; all values recorded at a speed of 60°/s.

		Mean Strengths Reported (Nm)		
		Perrin (1993)	Dvir (2004)	Present Study
Knee Ext.	(M)	212 - 259	257	163
	(F)	118	Not Available	106
Back Ext.	(M)	246 - 249 ‡	178 -237 ‡	292 †
	(F)	148 – 160 ‡	108 †	190 †
Shoulder Abd.	(M)	85 – 89	51 – 57	58
	(F)	43 – 50	27 – 29	31
Shoulder Ext.	(M)	53 – 90	80 – 118	66
	(F)	24 – 60	39 – 54	33

† Participants were in a seated posture for the recording of this strength value.

‡ Participants were in a semi-standing posture for the recording of values in this range of strength.

Table 4. Mean (±SD) values of back, knee, and shoulder extension, shoulder abduction, and total isokinetic strengths for the 32 subjects who completed the manual materials-handling experiment.

Gender	Joint Strengths (Nm)				
	Back Extension	Shoulder Abduction *	Shoulder Extension *	Knee Extension *	TIS
Men	283 ± 76	57 ± 11	64 ± 12	160 ± 40	844 ± 177
Women	198 ± 61	32 ± 8	34 ± 7	106 ± 43	543 ± 164
Both	240 ± 80	45 ± 16	49 ± 18	133 ± 49	694 ± 227

* Left and right sides averaged

Table 4 summarizes the strength data for the 32 asymptomatic subjects who completed the manual materials-handling experiment. A comparison between Table 2 and Table 4 suggests these 32 subjects were not a biased sample out of our entire asymptomatic group.

The experiment results suggest dynamic strength, as represented by the total isokinetic strength (TIS) score, had a significant effect on ACB_n for three of the batch sizes (n =4, 5, 6), as revealed by a type III analysis of effects in the logistic regression (see Table 5). The ACB_n tended to decrease as the TIS increased. This tendency is illustrated in Figure 5 for the case of n = 6. Note that completion of a batch in one carry occurred mostly in individuals with TIS greater than the mean (694 Nm). Parameter estimates of the TIS term in the logistic regression model for ACB_n (n =4, 5, 6) indicated that with an increase in TIS of 1 Nm, participants were .39%, .62%, and .74% more likely to choose lower values of ACB_4, ACB_5, and ACB_6, respectively (Karp, 2001.; Stokes et al., 1995). A type III analysis of effects revealed that TIS was a significant source of variance in ALC as well (see Table 5). Utilizing individual joint strength measurements as dependent variables in the logistic regression yielded effects similar to those observed with TIS. The correlation of strength measures at each of the joints with TIS resulted in r^2 values ranging from .8 to .9 (Table 6). No statistically significant interaction between TIS and gender was identified, suggesting that a separate analysis for males and females within each group was not necessary.

Table 5. The *p*-values from Type III analysis of effects using stepwise logistic regression.

Dependent Variable	Independent Variables		
	Total Isokinetic Strength	Knowledge of Strength	TIS-Gender Interaction Term
ACB_4	$p = 0.08$ *	$p = 0.58$	$p = 0.8357$
ACB_5	$p = 0.002$ **	$p = 0.036$ **	$p = 0.1127$
ACB_6	$p = 0.0006$ **	$p = 0.09$ *	$p = 0.1111$
ALC	$p = 0.0009$ **	$p = 0.088$*	$p = 0.1783$

* significant at α=.1; ** significant at α=.05.
Note that the *p*-values for TIS and knowledge of strength were from a regression analysis with the insignificant interaction term removed.

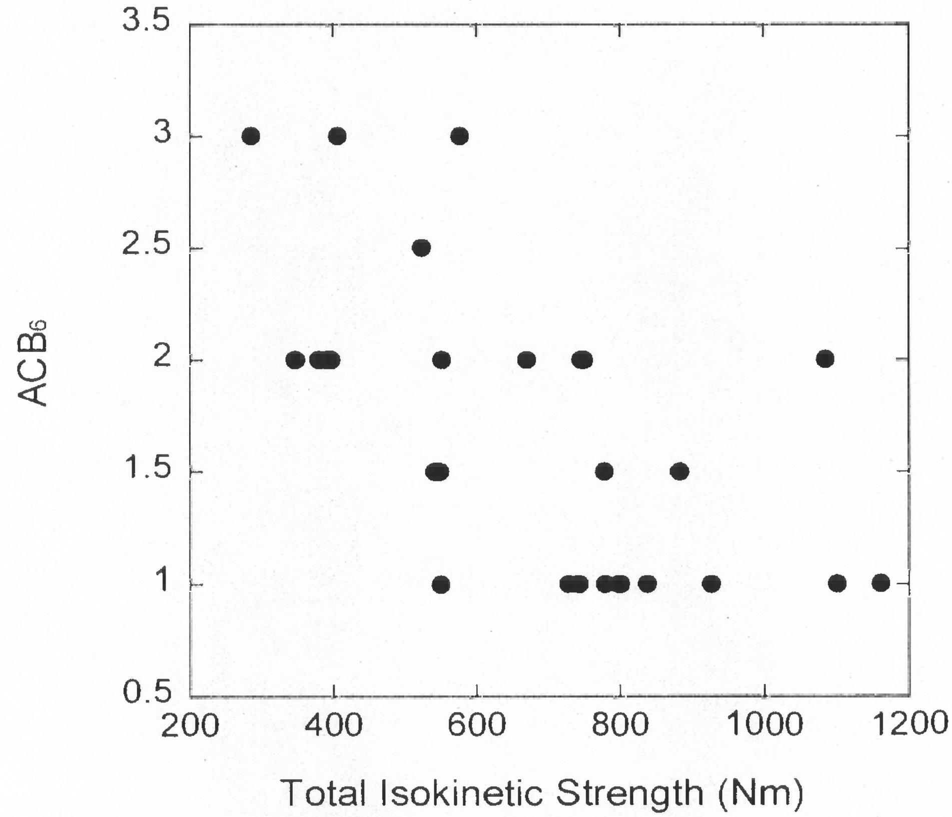


Figure 5. The average number of carries per batch of six (ACB_6) versus total isokinetic strength.

Table 6. The r^2 Values for representing correlations between strength variables.

	Shoulder Abduction*	Shoulder Extension*	Back Extension	Knee Extension*	TIS
Shoulder Abduction*	1				
Shoulder Extension*	0.92	1			
Back Extension	0.53	0.56	1		
Knee Extension*	0.71	0.61	0.61	1	
TIS	0.83	0.80	0.83	0.90	1

* Left and right sides averaged

The knowledge of strength had a statistically significant effect on ACB_5 (p = .036) and ACB_6 (p = .09), as shown in Table 4. Participants with knowledge feedback of their strength utilized a significantly lower number of carries than did those without, when handling batches of five and six plates (according to a Tukey mean separation test; $\alpha = .1$). The mean of ACB_5 and ACB_6 were 1.41 and 1.53, respectively, for those with knowledge of their strength, and were 1.75 and 1.84 for those without. Accordingly, ALC was higher for those with knowledge feedback of strength than for those without, although the difference was not found to be statistically significant; the mean values were 3.95 versus 3.42, respectively.

When the subjects are further divided according to their TIS scores—those with TIS scores in the upper half of the distribution ("stronger subject") and those with TIS scores in the lower half of the distribution ("weaker subject"), an interaction between the knowledge feedback and strength can be observed. As presented in Table 7, the differences in the average ACB_n and ACL values between the stronger and weaker participants are greater among those who did not receive knowledge feedback than among those who did. Therefore, we failed to reject the second hypothesis (H2).

Table 7. Mean ACB_n and ALC values for the two groups of participants, with each group separated into stronger (upper 50% in TIS) and weaker (lower 50% in TIS) halves.

Measure	Mean Values			
	Feedback Group		No-Feedback Group	
	Stronger (n=8)	Weaker (n=8)	Stronger (n=8)	Weaker (n=8)
ACB_4	1.06	1.25	1.06	1.44
ACB_5	1.38	1.44	[1.44]	[2.06]
ACB_6	[1.25]	[1.81]	[1.56]	[2.13]
ALC	4.29	3.60	[3.87]	[2.96]

[ ] Significantly different values according to a Tukey mean separation test (α=.1)

In estimating their strength abilities relative to the general population, participants averaged a rating of approximately 61st percentile. If the TIS score is accepted as representative of individual overall strength and the participant sample is assumed to be representative of the general population, then 21 of the 32 participants (11 in the Feedback Group and 10 in the No-Feedback Group) overestimated their strength with respect to the general population. The mean overestimate across the 21 participants averaged 26.95 percentile. All of the participants who underestimated their strengths were stronger individuals (i.e., TIS scores in the upper half). The mean of the actual percentile rankings for the TIS of those underestimating their strength was 80th percentile versus a mean of 34th for those overestimating their strengths. Differences in batch-assorting strategy, as defined by ACB_n and ALC, were observed between those underestimating and those overestimating their strengths, and these were primarily attributed to the difference in strength between the underestimating and overestimating participants.

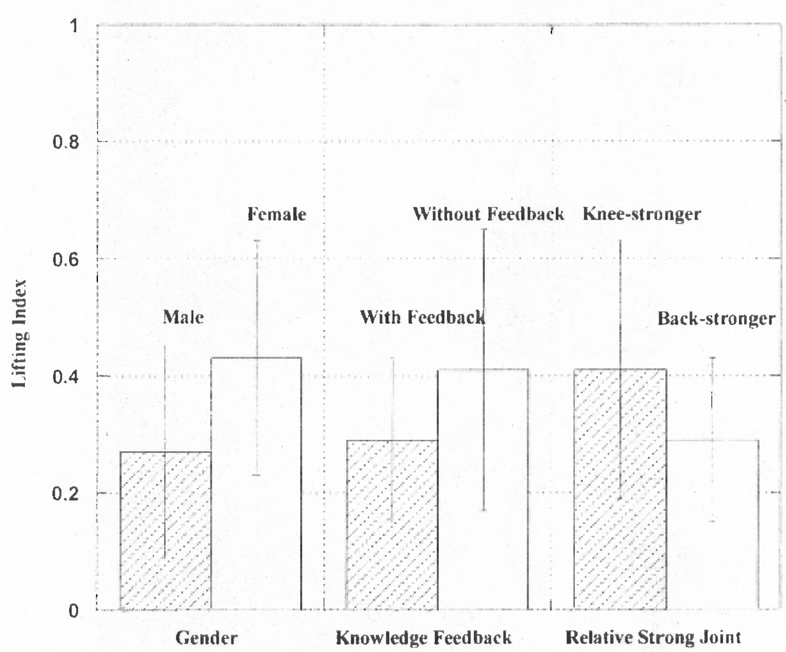


Figure 6. A comparison of mean lifting index values between gender, knowledge feedback, and relative stronger joint as summarized. Whiskers indicate the standard deviation.

The average lifting index (±SD) value across trials was 0.359 (±0.21) with a minimum equivalent to 0.001 and a maximum of 0.80—these were statistically summarized across all trials. Significant (α= 0.05) main effects of gender ($F(1, 81)=21.09$, $p<0.0001$), knowledge feedback ($F(1, 81)=5.84$, $p=0.0179$) and relative stronger joint ($F(1, 81)=9.71$, $p=0.0025$), on lifting index were observed in the two-way ANOVA. No significant effect of load magnitude on lifting index was found. Figure 6 compares the mean lifting index values between gender, knowledge feedback, and relative stronger joint. As the figure shows, relative stronger back and receiving knowledge feedback resulted in a small lifting index; i.e. subjects preferred back lifting. It also shows that the males tended to adopt smaller lifting indices than the females.

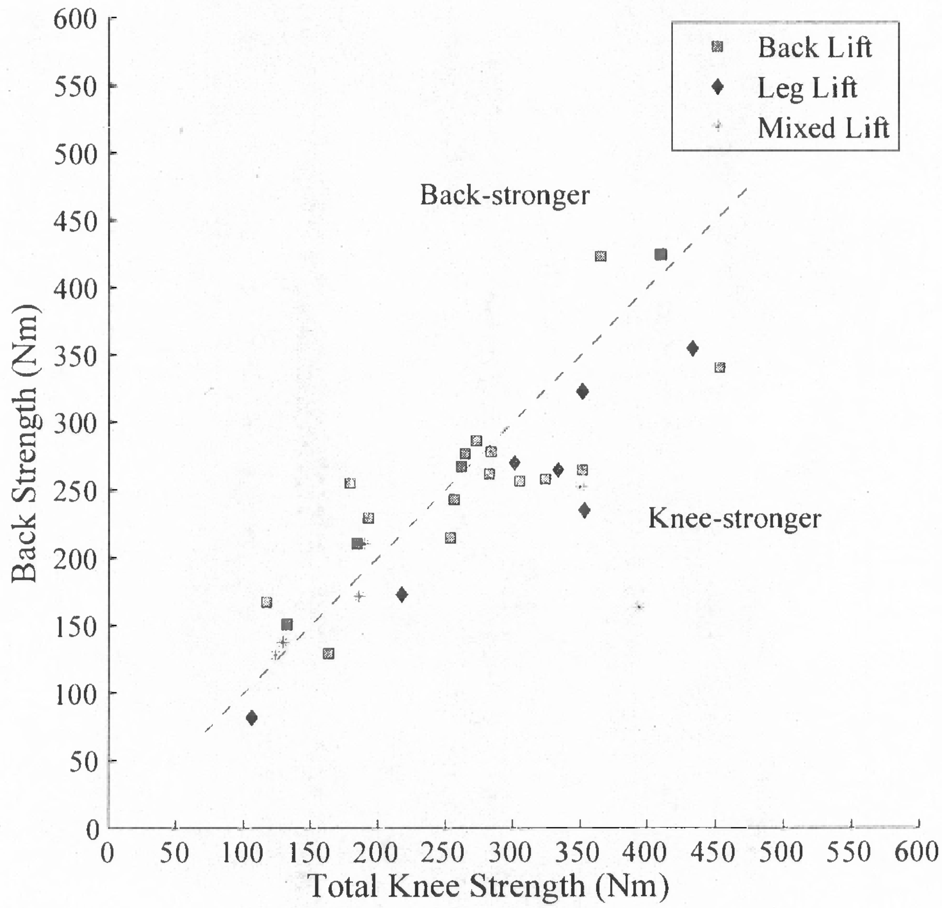


Figure 7. The distribution of lifting strategies used in handling a 5-lb load. Back Lift: LI (lifting index) < 0.38; Leg Lift: LI > 0.5; Mixed Lift: 0.38 ≤ LI ≤ 0.5.

The lifting strategies adopted by subjects of different back and total knee strengths are graphically illustrated in Figure 7. The ratio of the back strength versus the total knee strengths (graphically, the dashed diagonal line in Figure 7) does seem to generally separate the lifting strategies. Subjects with relatively greater back strength mainly used a back lift strategy, while subjects with relatively greater knee strengths used more varied strategies; however, leg lifts were exclusively adopted by subjects with relative stronger knee strength.

The above findings indicate that the strength factor may affect both the high-level decision making (e.g., what effort level to choose) and the low-level motor control (e.g., which body segment as the prime mover) during goal-driven (as opposed to passive) physical performance. The development of next generation digital human models ought to incorporate such factors in order to improve the realism and utility of the model-based simulation tools. Based on this concept, we therefore propose a new more holistic framework for digital human modeling and simulation integrating many consequential task and personal factors currently not considered as model inputs. Figure 8 illustrates the proposed framework, in which the left-side blocks and their interrelationships in fact constitute the conventional logic diagram of forward dynamic simulation of human movement production.

The proposed framework is a closed-loop system in which the feedback of current state (position and velocity) may influence not only the next state but also the musculotendon geometry, muscle force production, as well as the high-level neural excitation patterns. Of note also is that the limits on muscle force production (i.e., strengths) do not play a role explicitly in the movement dynamics unless the limits become active in performance at the maximum level.

The right-side blocks represent the two groups of factors that can affect the movement form and production, and ideally should be included as input variables in digital human modeling and simulation. Presently, however, only a limited subset of these factors is included. Anthropometry and gender are the only two personal attributes known to affect how a digital human and its movements are rendered at the lower geometrical and physical property levels. A host of additional personal factors including strength and other physical capacity limits, self-knowledge of the limits, and experience can exert influence on events of all levels in movement production, as demonstrated in our studies. Task characteristics affect how a movement task is initiated and sustained at the neural and muscular levels. Currently, only explicit directions or goals are implemented as command inputs (e.g., move forward, turn left) in simulation of a movement act. More implicit goals, such as intrinsic objective of minimizing a certain cost function (e.g., energy expenditure, muscle stress) are subjects of debates and not yet embodied in any existing simulation tools. Evidence has also accumulated to suggest a multitude of task factors including the load handled and speed in a lifting task can influence the movement behavior. Task duration certainly relates to muscle fatigue; however, the muscle fatigue effect on movement patterns has been difficult to model in digital human modeling.

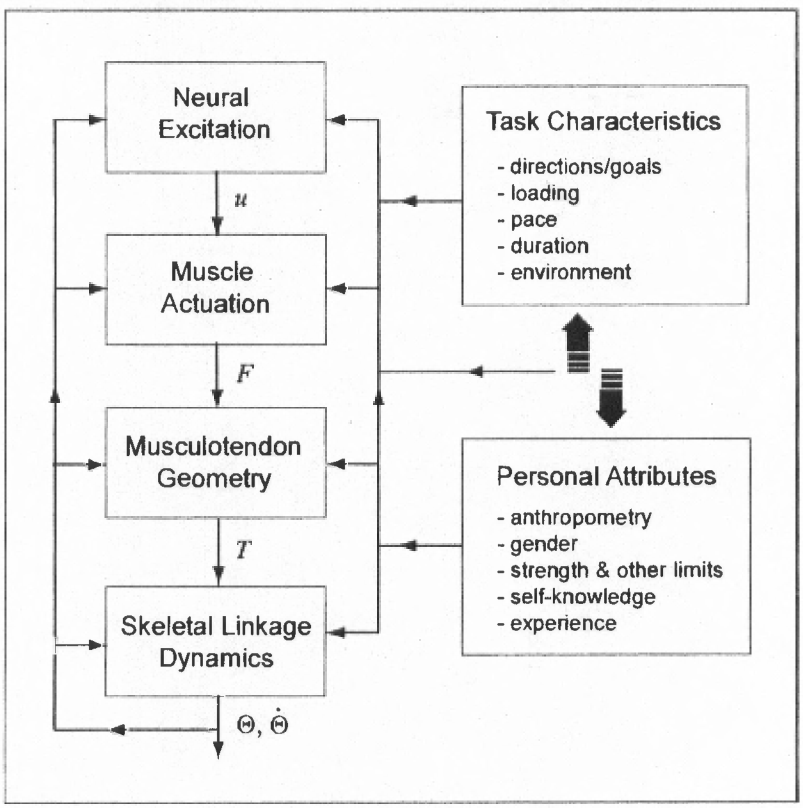


Figure 8. A new, more holistic framework for digital human modeling and simulation of physical performance involving movements.

Perhaps more important, the interaction between the task characteristics and personal attributes could play an important role in movement performance. As evidenced in the reported study, given load-pace requirement of a task, one may adapt to the best multi-level strategies to complete the task, taking into account one's physical capabilities and prior knowledge. Clearly, many of the effects outlined in the proposed framework remain poorly understood. We intend this new framework to guide our future investigations aimed to better understand and quantify these effects, one at a time, and then incorporate them into the next generation digital human models and ergonomic design tools.

A number of limitations of the study are acknowledged. First, we investigated still limited aspects of the highly complex and highly dynamic manual materials-handling. The dependent measures we designed and chose allowed simple quantification of the batch-assorting and lifting strategies. As they were more rudimentary descriptions of manual materials-handling performance, we felt any measures based on these descriptions (e.g., joint forces and torques derived using inverse dynamics) would be to "point out the obvious." Second, the total isokinetic strength (TIS) was created as a single index to represent the overall strength, and seemed to summarize well the individual joint strengths, as suggested by the correlation values (r^2 between .8 and .9). It however could be different from individual interpretations of the "overall strength capability" and from the real determining factor. The complex, multi-variate nature of strength as well as the categorical nature of dependent measures may have made it more difficult to achieve the statistical significance at the conventional α=.05 level. It is recognized that we were not able to distinguish the role of the shoulder joints (strength and movement). Third, although no statistically significant difference in strength was identified between the asymptomatic and self-claimed symptomatic groups, the data appeared to show a meager trend suggesting the asymptomatic subjects are overall stronger. Unfortunately, the limited resources and availability of participants who qualified our criteria did not permit a study with a significantly larger sample size. Fourth, the choice of a self-preferred pace in the experiment might limit the applicability of the findings. Time constraints under a real work setting may induce different strategies in terms of both pace-productivity decision and body mechanics.

Conclusion

In conclusion, the reported study investigated the relationship between dynamic (isokinetic) strength and the performance of manual materials-handling at both the decision making and lifting biomechanics levels. The study discovered that dynamic strength and self-knowledge of the strength could significantly affect the batch-assorting strategy to initiate a load handling task, and that the relative strength between the back and knees can differentiate and predict lifting biomechanics: persons with back strength greater than their total knee strength tended to use a back lift strategy, and vice versa. In establishing the databases to support the investigations, it also was found that there was no significant difference in dynamic strength between the asymptomatic subjects and self-claimed symptomatic subjects. The findings have important implications on the utility of isokinetic strength tests in worker selection or screening, on how job training and design should be conducted to better prevent injuries incurred during manual materials-handling, and on incorporation of strength factor in digital human modeling (DHM) technology for future ergonomics and design.

References

Andrews, A. W., Thomas, M. W., & Bohannon, R. W. (1996). Normative values for isometric muscle force measurements obtained with hand-held dynamometers. *Physical Therapy, 76*(3), 248-259.

Balogun, J. A., Olawoye, A. G., & Oladipo, V. A. (1991). Isometric back strength in different age groups. *International Disability Studies, 13*(3), 87-90.

Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory.* Englewood Cliffs, NJ: Prentice-Hall.

Brownsword, A. W. (1987). *It takes all types.* San Bernadino: HRM Press.

Burgess-Limerick, R., & Abernethy, B. (1997). Toward a quantitative definition of manual lifting postures. *Human Factors, 39*(1), 141-148.

Cady, L. D., Bischoff, D. P., O'Connell, E. R., Thomas, P. C., & Allan, J. H. (1979). Strength and fitness and subsequent back injuries in firefighters. *Journal of Occupational Medicine, 21*(4), 269-272.

Chaffin, D. B. (1974). Human strength capability and low-back pain. *Journal of Occupational Medicine, 16*(4), 248-254.

Chaffin, D. B., Andersson, G. B. J., & Martin, B. J. (1999). *Occupational Biomechanics* (3 ed.). New York: John Wiley & Sons.

Chaffin, D. B., Herrin, G. D., & Keyserling, W. M. (1978). Preemployment strength testing: an updated position. *Journal of Occupational Medicine, 20*(6), 403-408.

Chaffin, D. B., & Park, K. S. (1973). A longitudinal study of low-back pain as associated with occupational weight lifting factors. *American Industrial Hygiene Association Journal, 34*(12), 513-525.

Chirikos, T. N., & Nestel, G. (1985). Longitudinal analysis of functional disabilities in older men. *Journal of Gerontology, 40*(4), 426-433.

Ciriello, V. M., & Snook, S. H. (1983). A study of size, distance, height, and frequency effects on manual handling tasks. *Human Factors, 25*(5), 473-483.

Dunn, K., & Dawson, E. (1994). The right person for the job. *Occupational Health and Safety Canada, 10*, 28-30.

Dvir, Z. (2004). *Isokinetics: Muscle Testing, Interpretation and Clinical Applications*. Edinburgh: Churchill Livingstone.

Garg, A., Mital, A., & Asfour, S. S. (1980). A comparison of isometric strength and dynamic lifting capability. *Ergonomics, 23*(1), 13-27.

Genaidy, A. M., Karwowksi, W., Guo, L., Hidalgo, J., & Garbutt, G. (1992). Physical training: a tool for increasing work tolerance limits of employees engaged in manual handling tasks. *Ergonomics, 35*(9), 1081-1102.

Genaidy, A. M., Karwowski, W., Christensen, D. M., Vogiatzis, C., Deraiseh, N., & Prins, A. (1998). What is 'heavy'? *Ergonomics, 41*(4), 420-432.

Heijden, F. v. d., Duin, R. P. W., Ridder, D. d., & Tax, D. M. J. (2004). *Classification, Parameter Estimation and State Estimation: An Engineering Approach using Matlab*. England: John Wiley& Sons Ltd.

Hughes, R. E., Johnson, M. E., O'Driscoll, S. W., & An, K. N. (1999a). Age-related changes in normal isometric shoulder strength. *American Journal of Sports Medicine, 27*(5), 651-657.

Hughes, R. E., Johnson, M. E., O'Driscoll, S. W., & An, K. N. (1999b). Normative values of agonist-antagonist shoulder strength ratios of adults aged 20 to 78 years. *Archives of Physical Medicine and Rehabilitation, 80*(10), 1324-1326.

Jackson, A. S., & Sekula, B. K. (1999). The influence of strength and gender on psychophysical lift capacity. *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, 723-727.

Karwowski, W., Lee, W., Jamaldin, B., Gaddie, P., Jang, R. L., & Alqesaimi, K. K. (1999). Beyond psychophysics: the need for a cognitive engineering approach to setting limits in manual lifting tasks. *Ergonomics, 42*(1), 40-60.

Karwowski, W., & Yates, J. W. (1986). Reliability of the psychophysical approach to manual lifting of liquids by females. *Ergonomics, 29*(2), 237-248.

Kishino, N. D., Mayer, T. G., Gatchel, R. J., Parrish, M. M., Anderson, C., Gustin, L., et al. (1985). Quantification of lumbar function. Part 4: Isometric and isokinetic lifting simulation in normal subjects and low-back dysfunction patients. *Spine, 10*(10), 921-927.

Kovar, M. G., & LaCroix, A. Z. (1987). Aging in the eighties, ability to perform work-related activities. *Advance Data, 136*, 1-11.

Kuo, A. D., & Zajac, F. E. (1993). A biomechanical analysis of muscle strength as a limiting factor in standing posture. *Journal of Biomechanics, 26 Suppl. 1*, 137-150.

Langrana, N. A., Lee, C. K., Alexander, H., & Mayott, C. W. (1984). Quantitative assessment of back strength using isokinetic testing. *Spine, 9*(3), 287-290.

Li, K., & Zhang, X. (2007). The Strength Factor in Digital Human Modeling and Simulation: A Case for a New Framework. *Proceeding of the 1st international digital human modeling conference*, 144-146.

Mandell, P. J., Weitz, E., Bernstein, J. I., Lipton, M. H., Morris, J., Bradshaw, D., et al. (1993). Isokinetic trunk strength and lifting strength measures. Differences and similarities between low-back-injured and noninjured workers. *Spine, 18*(16), 2491-2501.

Marras, W. S. (2000). Occupational low back disorder causation and control. *Ergonomics, 43*(7), 880-902.

Mital, A. (1987). Patterns of Differences between the Maximum Weights of Lift Acceptable to Experienced and Inexperienced Materials Handlers. *Ergonomics, 30*(8), 1137-1147.

Mooney, V., & Andersson, G. B. (1994). Trunk strength testing in patient evaluation and treatment. *Spine, 19*(21), 2483-2485.

Murray, M. P., Duthie, E. H., Jr., Gambert, S. R., Sepic, S. B., & Mollinger, L. A. (1985). Age-related differences in knee muscle strength in normal women. *Journal of Gerontology, 40*(3), 275-280.

Murray, M. P., Gardner, G. M., Mollinger, L. A., & Sepic, S. B. (1980). Strength of isometric and isokinetic contractions: knee muscles of men aged 20 to 86. *Physical Therapy, 60*(4), 412-419.

Newton, M., & Waddell, G. (1993). Trunk strength testing with iso-machines. Part 1: Review of a decade of scientific evidence. *Spine, 18*(7), 801-811.

Nicholson, L. M., & Legg, S. J. (1986). A Psychophysical Study of the Effects of Load and Frequency Upon Selection of Workload in Repetitive Lifting. *Ergonomics, 29*(7), 903-911.

Parcell, A. C., Sawyer, R. D., Tricoli, V. A., & Chinevere, T. D. (2002). Minimum rest period for strength recovery during a common isokinetic testing protocol. *Medicine and Science in Sports and Exercise, 34*(6), 1018-1022.

Perrin, D. H. (1993). *Isokinetic Exercise and Assessment*. Champaign, IL: Human Kinetics.

Poulsen, E. (1981). Back muscle strength and weight limits in lifting burdens. *Spine, 6*(1), 73-75.

Pytel, J. L., & Kamon, E. (1981). Dynamic strength test as a predictor for maximal and acceptable lifting. *Ergonomics, 24*(9), 663-672.

Rice, C. L., Cunningham, D. A., Paterson, D. H., & Rechnitzer, P. A. (1989). Strength in an elderly population. *Archives of Physical Medicine and Rehabilitation, 70*(5), 391-397.

Ryan, A. M., Greguras, G. J., & Ployhart, R. E. (1996). Perceived job relatedness of physical ability testing for firefighters: Exploring variations in reactions. *Human Performance, 9*(3), 219-240.

Smeesters, C., Hayes, W. C., & McMahon, T. A. (2001). The threshold trip duration for which recovery is no longer possible is associated with strength and reaction time. *Journal of Biomechanics, 34*(5), 589-595.

Thelen, D. G., Wojcik, L. A., Schultz, A. B., Ashton-Miller, J. A., & Alexander, N. B. (1997). Age differences in using a rapid step to regain balance during a forward fall. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 52*(1), M8-13.

Vandervoort, A. A., Hayes, K. C., & Belanger, A. Y. (1986). Strength and endurance of skeletal muscle in the elderly. *Physiotherapy Canada, 38*, 167-173.

Vandervoort, A. A., Kramer, J. F., & Wharram, E. R. (1990). Eccentric knee strength of elderly females. *Journal of Gerontology, 45*(4), B125-128.

Whipple, R. L. (1987). Risk factors for falling in the elderly. *Journal of American Geriatric Society, 35*, 13-20.

Wilde, G. J. (1998). Risk homeostasis theory: an overview. *Injury Prevention, 4*(2), 89-91.

Wilmarth, M. A., & Herekar, R. (1991). Lifting ability and leg strength. *Journal of Orthopaedic and Sports Physical Therapy, 14*(1), 24-30.

Wojcik, L. A., Thelen, D. G., Schultz, A. B., Ashton-Miller, J. A., & Alexander, N. B. (1999). Age and gender differences in single-step recovery from a forward fall. *Journals of Gerontology Series A: Biological and Medical Sciences, 54*(1), M44-50.

Young, A., Stokes, M., & Crowe, M. (1984). Size and strength of the quadriceps muscles of old and young women. *European Journal of Clinical Investigation, 14*(4), 282-287.

Young, A., Stokes, M., & Crowe, M. (1985). The size and strength of the quadriceps muscles of old and young men. *Clinical Physiology, 5*(2), 145-154.

Publications

Journal Articles

Bartlett D, Li K, Zhang X: [2007] A Relation between Dynamic Strength and Manual Materials-handling Strategy Affected by Knowledge of Strength. Human Factors 49: 438-446

Riemer R, Hsiao-Wecksler ET, Zhang X: [2008] Uncertainties in Inverse Dynamics Solutions: A Comprehensive Analysis and an Application to Gait. Gait and Posture, in press

Conference Proceedings

Riemer R, Lee SW, Zhang X: [2004] Full Body Inverse Dynamics Solutions: An Error Analysis and a Hybrid Approach. Proceedings of the 28th American Society of Biomechanics Annual Meeting, Portland, OR

Riemer R, Hsiao-Wecksler ET, Zhang X: [2005] An Analysis of Uncertainties in Inverse Dynamics Solutions for Gait. Proceedings of the XXth Congress of the International Society of Biomechanics & 29th American Society of Biomechanics Meeting, Cleveland, OH

Bartlett DB, Li K, Zhang X: [2006]: Dynamic Strength and Knowledge of Strength Affect Manual Materials Handling Strategy. Proceedings of National Occupational Research Agenda (NORA) Symposium, Washington DC

Li K, Zhang X: [2007] The Strength Factor in Digital Human Modeling and Simulation: A Case for a New Framework. Proceedings of the 1st International Conference on Digital Human Modeling, Beijing, China

Li K, Zhang X: [2008] Can Relative Strength between the Back and Knees Differentiate Lifting Strategy? Submitted to the Human Factors & Ergonomics Annual Meeting

Dissertation/Thesis

Bartlett D: [2005] Isokinetic Strength: A Database and Analysis of its Relation with Manual Materials Handling Strategy, M.S. Thesis, University of Illinois at Urbana-Champaign

Inclusion of Gender and Minority Study Subjects

See Appendix E.

Inclusion of Children

N/A

Materials Available for Other Investigators

N/A

If you have

Knee, Back, or Shoulder pain

and are between 20 and 45…

WE NEED YOU!

Research is being conducted in the *Department Mechanical & Industrial Engineering* at the *University of Illinois*, and if you are experiencing *chronic* pain in your knees, back, or shoulders, we want you to participate.

You will be paid $30 for the first hour and $10 for each additional hour.

You will be asked to perform a strength test and several light-weight lifting tasks.

If you are interested in participating, or have any questions please send an email to:
biomech_ergo@yahoo.com

Appendix B. Subject Consent Form

Project Title: Effects of Shoulder, Low Back, or Knee Strength Degradation on Motion Control Strategies and Injury Risk During Manual Materials Handling

Principal Investigator: Xudong Zhang, Ph.D., Department of Mechanical & Industrial Engineering, University of Illinois at Urbana-Champaign

The purpose of this study is to investigate whether your shoulder, knee, and back strengths affect how you move when lifting a weight. There are several potential benefits of this study, including: (1) it will provide a better understanding of what internally determines your movement pattern during lifting activities; (2) it may help develop a clinical application that uses movement information to diagnose strength-related problems; (3) the data acquired in this study can also serve as the basis for simulating human movement on computer.

If you are able to perform moderate manual activities such as lifting a 20-pound weight from the floor, under no prohibition against engaging in vigorous exercise, and agree to participate, you will be involved in one or both of the two sessions in this study. The total duration of these two sessions is not expected to exceed 4 hours. Before you actually begin the sessions, an experimenter will first take some anthropometric measures such as the lengths of your arms and legs, your stature and weight.

The first session includes measurements of your strength of trunk, knee, and shoulder muscles. You will start by warming up your body on the strength testing apparatus. You will then be asked to perform maximum voluntary contractions in different speeds and postures with your shoulder, knee, or trunk muscles. These measures will be acquired using a strength testing facility. You will be using a normal seated position while the strength measures are taken.

Based on the results from the strength testing, you may be asked to participate in the second session of the study. In this session, you will be performing lifting movement tasks. You will be asked to lift a box from the floor to approximately knuckle and possibly shoulder height. The box will have the following weights: 5 lbs, 10 lbs, 15 lbs, and 20 lbs; those who do not score adequately on the test, or whose pain is significant, will lift only the empty box. You will only need to lift the weights that you feel you are capable of lifting safely. You will have practices to be familiarized with the weights and the tasks in general. Prior to the start of lifting movements, an experimenter will place reflective surface markers on some of your body joints. This placement will involve touching the following areas of your body: wrists, elbows, shoulders, hips, upper and lower back around the spine, knees, ankles, and feet. In order to put the reflective markers on you to accurately measure your movements, you will be asked to wear a tank top and tight-fit shorts. The reflective surface marker locations will be recorded by a multi-camera system and stored in the computer. In addition, digital camera or video may be used to record some of your movements. This information will only be used by the researchers (the principal investigator and student research assistants) to aid in the analysis of your movement data and will remain strictly confidential. In case the video or photo information is used in professional presentations or publications (please check the box at the end of the consent form to indicate whether you permit such use), your identity will be concealed in an appropriate manner.

The risk of this study includes possible muscle soreness. The possibility of physical injury is very low. You will be compensated $10 for each hour you are involved in this study. Your participation is voluntary. You may discontinue your participation at any time. In the event you elect to discontinue, you will be paid for the time you have participated, prorated to the next closest half-hour. The records of your participation and data files will be confidential. A coding system will be used so that when the researchers (the principal investigator and student research assistants) of this study access your data files, your name will not be associated with your data.

You have the right and are encouraged to ask questions at any time. You can contact Xudong Zhang (217-265-8031) and the Executive Secretary of the Institutional Review Board, UIUC, (217-333-2670) for questions about the research and research subject's rights, respectively. You may also contact the Carle Institutional Review Board (217-383-4366).

UNIVERSITY OF ILLILNOIS
AT URBANA-CHAMPAIGN

Department of Mechanical and Industrial Engineering

College of Engineering
140 Mechanical Engineering Building, MC-244
1206 West Green Street
Urbana, IL 61801

RESEARCH SUBJECT'S CONSENT

Project Title: Effects of Shoulder, Low Back, or Knee Strength Degradation on Motion Control Strategies and Injury Risk During Manual Materials Handling

I have read or have had read to me all of the above descriptions of this research project. I have been told of the risks and discomforts associated with the study. All my questions about my participation in this study have been answered to my satisfaction.

I understand that in the event of unlikely physical injury resulting from the research procedures, no compensation will be provided by the University of Illinois except as required by law. I also understand that emergent medical treatment is available, if necessary, but at my own expense.

I understand that my participation in this study is voluntary and I may discontinue at any time without any penalty or loss of benefits to which I am otherwise entitled. I am under no pressure to participate. I understand that I will be given a copy of the full consent form.

☐ I do permit the use of video or photo data of my performance in professional presentations or publications.

☐ I do not permit the use of video or photo data of my performance in professional presentations or publications.

SIGNATURE OF SUBJECT ______________________ DATE ______________________

SIGNATURE OF WITNESS ______________________ DATE ______________________

SIGNATURE OF INVESTIGATOR ______________________ DATE ______________________

Appendix C. Subject Strength Testing Questionnaire

Subject Information

Contact and Descriptive Information

Please complete the following information about yourself.

Name* Last ______ First ______ Middle ______

Address* Street ______ Apt. ______
City ______ State ______ Zip ______

Phone* (###) ###-#### ______ SSN* ###-##-#### ______

Email* ______

Date of Birth* MM/DD/YYYY ______

Height Inches ______

Weight lbs ______

* *Denotes personal information – this information will not be shared.*

Classification Information

Place an X in the box next to all of the applicable responses to the following classifications.

a. **Sex**
[ ] Male
[ ] Female

b. **Ethnicity**
[ ] Hispanic or Latino
[ ] Not Hispanic or Latino

c. **Race**
[ ] American Indian/Alaska Native
[ ] Asian
[ ] Native Hawaiian or Other Pacific Islander
[ ] Black
[ ] White

Health Information

Place an X in the box next to the appropriate answer for each of the following questions.

d.	[ ] Yes [ ] No	**Are you currently experiencing chronic pain in any of the joints in your body?** *(if No, skip ahead to **i**)*
e.	**If you answered yes to d, in which (if any) of the joints below do you experience pain?**	[ ] Knee [ ] Left [ ] Right [ ] Lower Back [ ] Shoulder [ ] Left [ ] Right
f.	[ ] Yes [ ] No	**Has this pain persisted for six (6) months or more?**
g.	[ ] Yes [ ] No	**Is the pain which you are experiencing related to an acute injury?** *(e.g. an accident, an injury, other trauma)*

h. **How would you rate the level of pain which you are now experiencing?**

[ ] 0 No symptoms
[ ] 1 Minimal symptoms. Easily able to ignore.
[ ] 2 Minimal to mild symptoms. Aware of symptom, noticeable when performing daily tasks.
[ ] 3 Mild symptoms. Annoying, noticeable when performing daily tasks.
[ ] 4 Mild to moderate symptoms. Requires medication on occasion.
[ ] 5 Moderate symptoms. Req. meds, sleep disturbed, avoid daily tasks on occasion (25%).
[ ] 6 Moderate to severe symptoms. Irritable, sleep disturbed, avoid daily tasks freq. (75%).
[ ] 7 Severe symptoms. Unable to perform daily tasks and unable to perform job.
[ ] 8 Severe symptoms. Unable to bath/toilet, partial bedrest, assistance req. to leave home.
[ ] 9 Total bedrest. May pass out.
[ ] 10 Call ambulance.

i.	[ ] Yes [ ] No	**Do you have any type of cardio-respiratory disorder?**
j.	[ ] Yes [ ] No	**Do you have diabetes?**
k.	[ ] Yes [ ] No	**Do you have any other chronic illnesses/disorders?**

l. **Please list any chronic illnesses below if you answered Yes to k.**

____

m. **How would you rate the physical activity associated with your work?**

[ ] 5 Strenuous - continuous heavy exertions, bending/awkward postures, always moving
[ ] 4 Hard - discontinuous exertions, some bending/stooping, moving at most times
[ ] 3 Moderate - involving some physical activity, standing or moving much of the time
[ ] 2 Low - involving little physical activity, mostly seated work
[ ] 1 Light - almost exclusively seated, no physical exertion
[ ] 0 None - don't work

n. **How would you rate your over-all fitness level?**

[ ] 1 Excellent
[ ] 2 Good
[ ] 3 Average
[ ] 4 Below Average
[ ] 5 Poor

---

o. **How much time do you spend exercising in the average week?**

[ ] More than 9 hours
[ ] More than 7 but no more than 9 hours
[ ] More than 5 but no more than 7 hours
[ ] More than 3 but no more than 5 hours
[ ] More than 1 but no more than 3 hours
[ ] Less than 1 hour

---

p. [ ] Yes **Do you feel that you are able to safely lift 20 lbs?**
[ ] No

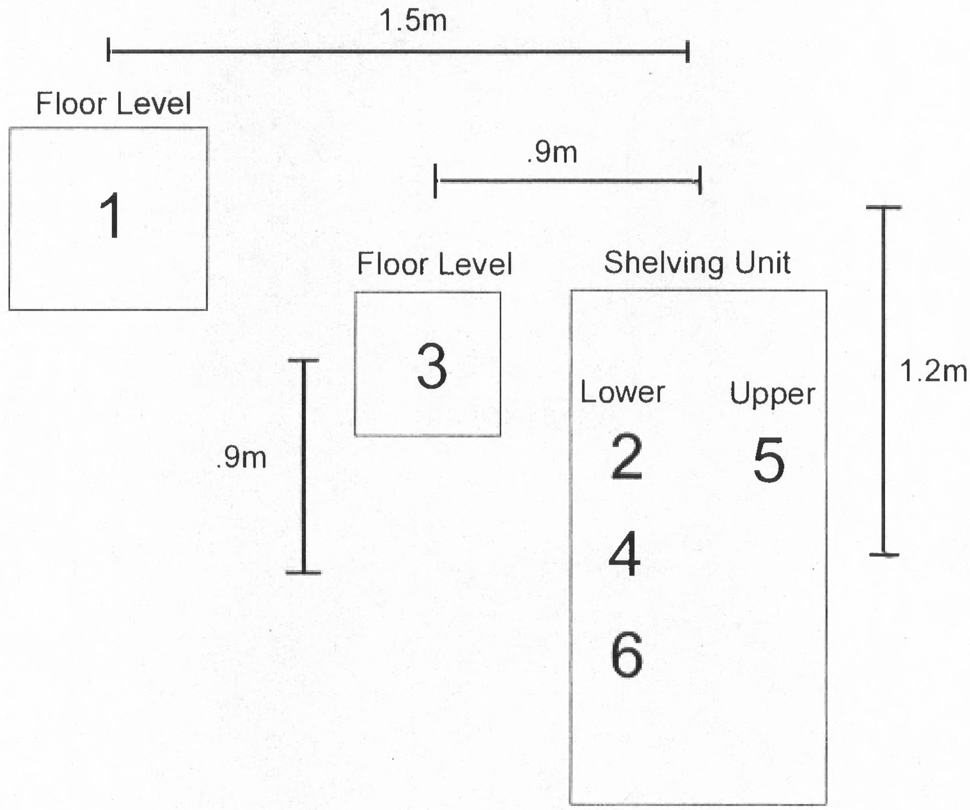
---

q. [ ] RH **Are you right-handed or left-handed?**
[ ] LH

---

r. [ ] Yes **Would you be willing to participate in future studies related to this one?**
[ ] No

Appendix D. Layout of the Experimental Area for the Lifting Task



D.1. Map View of Experimental Area (not to scale)

The task begins with the crate at 1.

The subject removes the crate to 2 - the lower shelf of the shelving unit. (Please note that 2, 4, and 6 on this diagram are not correctly spatially located, but represent the same position – approximately the center of the lower shelf on the shelving unit – only at different times.)

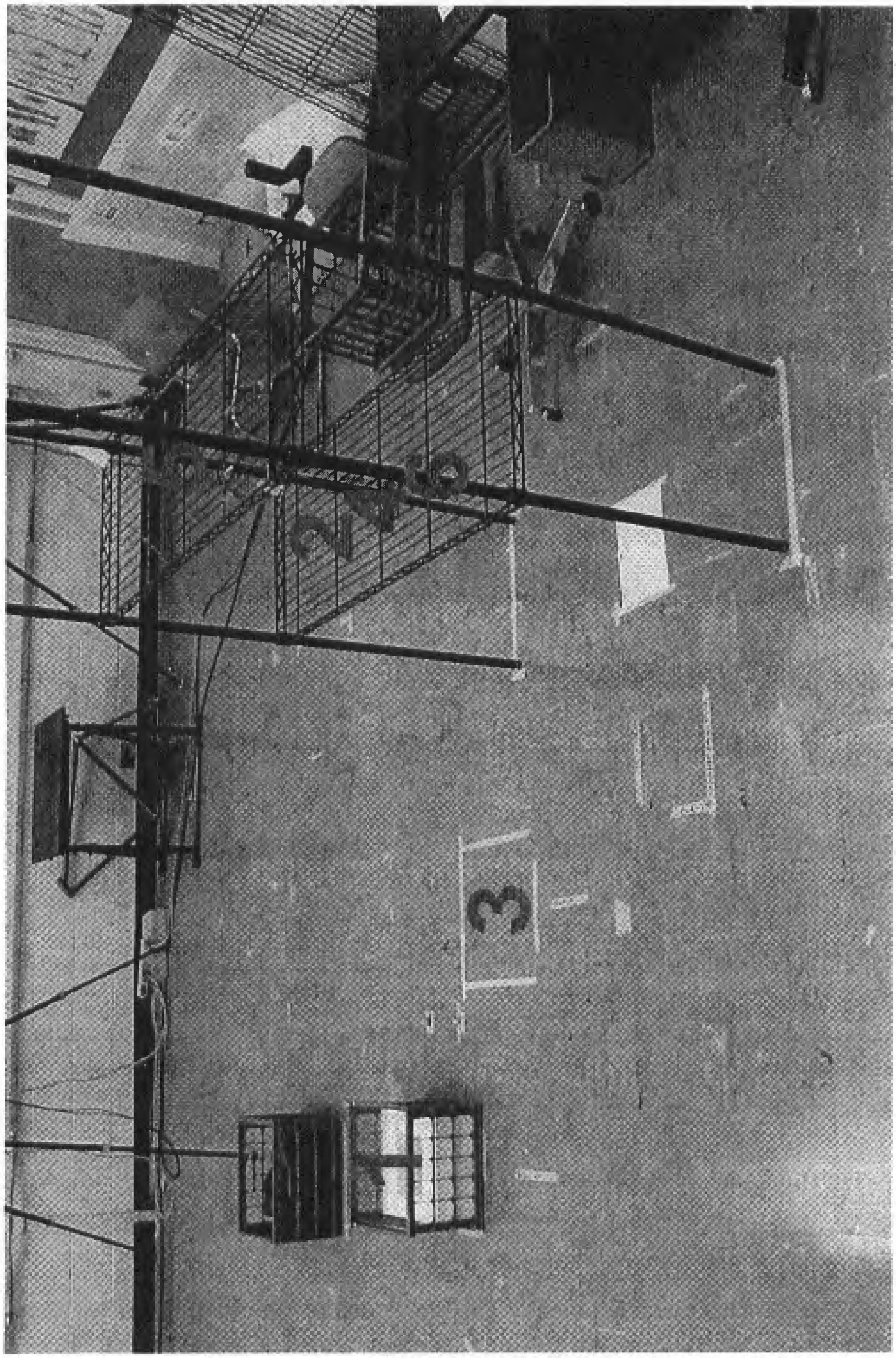
In the third movement, the subject moves the crate to 3 on the floor.

The subject continues by moving the crate to 4 – the lower shelf.

The subject then moves the crate to 5 on the upper shelf of the shelving unit. (Again note that 5 is not correctly spatially located, but is on the upper shelf of the unit directly above 4 – in the approximate center of the upper shelf.)

In the final movement, the subject moves the crate to 6.

D.2. Pictorial View of Experimental Area



Appendix E. Inclusion Enrollment report (PHS 2590 form)

Principal Investigator/Program Director (Last, First, Middle): Zhang, Xudong

Inclusion Enrollment Report

This report format should NOT be used for data collection from study participants.

Study Title: Effects of shoulder, low back, or knee strength degradation on motion control strategies& injury risk

Total Enrollment: 64 **Protocol Number:** 00054

Grant Number: K01 OH007838

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
	Sex/Gender			
Ethnic Category	**Females**	**Males**	**Unknown or Not Reported**	**Total**
Hispanic or Latino	1	2	0	3 **
Not Hispanic or Latino	27	33	0	60
Unknown (individuals not reporting ethnicity)	1	0	0	1
Ethnic Category: Total of All Subjects*	29	35	0	64 *
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	5	2	0	7
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	3	6	0	9
White	21	25	0	46
More Than One Race	0	0	0	0
Unknown or Not Reported	0	2	0	2
Racial Categories: Total of All Subjects*	29	35	0	64 *

PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	**Females**	**Males**	**Unknown or Not Reported**	**Total**
American Indian or Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	1	0	0	1
White	0	0	0	0
More Than One Race	0	0	0	0
Unknown or Not Reported	0	2	0	2
Racial Categories: Total of Hispanics or Latinos**	1	2	0	3 **

* These totals must agree.
** These totals must agree.