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The relationship between cumulative low back loads and heart rate determined physical activity level during non-occupational tasks.

Nadia R. Azar
University of Windsor

The Relationship Between Cumulative Low Back Loads and Heart Rate Determined Physical Activity Level During Non-occupational Tasks

by:
Nadia R. Azar

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ABSTRACT

Nadia R. Azar
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The Relationship Between Cumulative Low Back Loads and Heart Rate Determined Physical Activity Level During Non-occupational Tasks

The aim of this study was to quantify the relationship between heart rate determined physical activity levels (HR-PAL), and estimates of cumulative low back loads estimated from video records of non-occupational activities. Subjects were videotaped while performing self-determined, non-occupational activities within their own homes, for a period of 2 hours. Subject HR was continuously recorded during the data collection period. The 2-hour HR profile, along with subjects' height, mass, age, gender, and median sitting HR, were used as inputs into a regression-based mathematical model to estimate HR-PAL. The video data were captured to digital format at 3 samples/sec; the video was trimmed to match the heart rate file, and each task was then trimmed out into separate video image clips. The video clips were analyzed with the 3-D Match video analysis tool. At an alpha level of 0.05, quadratic regression equations were able to account for a significant amount of variance in cumulative compression force (R^2=0.817), cumulative flexion moment (R^2=0.757), and cumulative right axial twist moment (R^2=0.769). Significant differences were found between predicted and actual compression force (t=-3.502, p=0.04), joint anterior shear force (t=-22.527, p = 0.00), reaction anterior shear force (t=-17.471, p=0.00), and flexion moment (t=-14.016, p = 0.00). When an alpha level of 0.1 was used, quadratic regression equations were able to account for a significant amount of variance in four

additional cumulative output variables: cumulative reaction anterior shear force (R^2=0.573), cumulative extension moment (R^2=0.492), cumulative left lateral bend moment (R^2=0.535), and cumulative left axial twist moment (R^2=0.492). Significant differences were also found between predicted and actual joint anterior shear force (t = -2.437, p = 0.09). While HR-PAL shows promise in its ability to predict cumulative L4/L5 spine loading, further investigation of this relationship is needed.

DEDICATION

This thesis is dedicated to my family.
To my parents, Gerry and Maureen Oglan, whose achievements were my inspirations for pursuing this degree, and to my husband Dory Azar, whose love and support enabled me to finish it.

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Chapter I
Introduction

Peak joint loads have been previously used to predict the risk of reporting low back pain (LBP; Fig. 1). Although tolerance limit values for peak loading have been established, low back problems continue to pose a significant problem in occupational settings. The cumulative load on the low back has recently been identified as a significant risk factor for reporting LBP (Kumar, 1990; Norman et al., 1998; Daynard et al., 2001; Kerr et al., 2001). While evidence in support of cumulative loads as a risk factor for LBP is mounting, current methods of collecting and processing cumulative load data remain expensive and time consuming, despite recent efforts to reduce the financial and time costs (Callaghan et al., 2001; Neumann et al., 2001; Andrews and Callaghan, 2003).

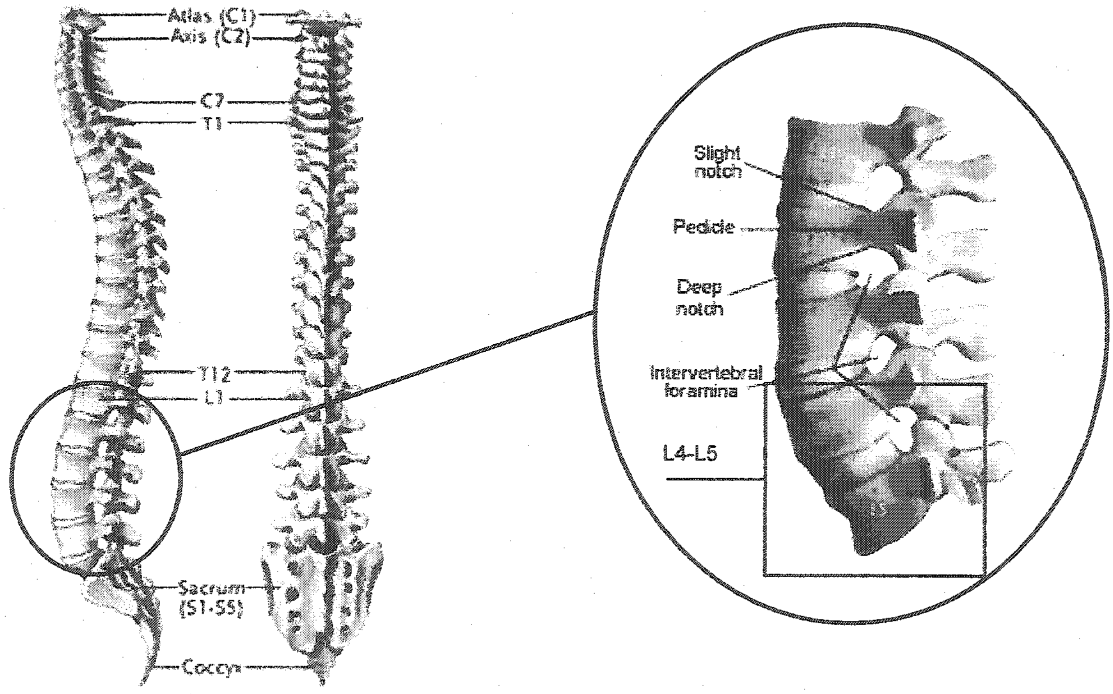

Figure 1: The Spinal Column and the Lumbar Vertebrae. Compression of the lumbar spine often results in LBP. Of particular concern is the joint between the fourth and fifth lumbar vertebrae, which undergoes the highest magnitudes of compression.

Self-report measures are attractive tools for data collection in large-scale studies because they allow researchers to collect a large amount of data at a low cost and in a relatively short time. However, there is mixed sentiment in the literature regarding the validity and reliability of self-report measures (Burdorf and Laan, 1991; Van der Beek et al., 1994; Andrews et al., 1997). A more objective method to quantify cumulative spine loads is the lumbar motion monitor (Marras et al., 1992). The lumbar motion monitor (LMM) is a triaxial electrogoniometer, which acts as an exoskeleton to the thoracolumbar spine (approximately T7-S2). It records the instantaneous position, velocity, and acceleration of the trunk relative to the pelvis in three dimensions, throughout a task. Although the LMM has been shown to be very reliable and accurate (Marras et al., 1992, Gill and Callaghan, 1996), subjects using the LMM will be limited in the activities they can perform because the signals from the electrogoniometer are continuously downloaded onto a computer. Also, video documentation is still required to record the position of the hands. This, in addition to the significant cost of the unit, prohibits the use of the LMM in field studies involving non-repetitive tasks.

Much of the research on low back loading, both peak and cumulative, has been performed in occupational settings. However, some research has shown that significant loads are being incurred during non-occupational activities, such as mowing the lawn (Fig. 2) making a bed, folding laundry, or vacuuming (Milburn and Barrett, 1999; Lauder and Andrews, 2002; Lauder, et al., 2002; Azar et al., 2003; Godin et al., 2003). Lengthy data collections and the need for video documentation are part of the reason for the limited data of this nature in the

Figure 2: Sample Non-occupational Activity. Non-occupational activities observed in the present study included yard work (mowing the lawn, opening a pool, etc.), housework (vacuuming, doing laundry, etc.), and leisure activities (reading, watching television, etc.).

literature to date. If it were possible to eliminate the need for video documentation, collection of cumulative load data would be greatly facilitated.

The need for an objective, cost-effective, and reliable method of data collection has lead to the consideration of a potential relationship between individuals' levels of energy expenditure during non-occupational activities, and their associated cumulative low back loads. If more physically active individuals experience a broader range of postures and loading situations than sedentary individuals, and since energy expenditure is related to physical activity level (Ainsworth et al., 2000), then the level of energy expenditure during non-occupational activities may provide an indication of the associated cumulative loads.

Several methodologies exist for quantifying energy expenditure, including doubly labeled water, self-report questionnaires, motion sensors (accelerometers), and heart rate monitoring. Heart rate monitoring is objective, non-invasive, and relatively inexpensive, and is known to be a strong predictor of energy expenditure (Strath et al., 2000). Recent work by Rennie et al. (2001) has eliminated the need for individual heart rate/oxygen consumption (HR/VO_2) calibration curves in order to predict energy expenditure (EE) from heart rate. Using this approach, physical activity level is expressed as the ratio of total energy expenditure to resting energy expenditure; values which can easily be predicted from a few simple measures such as age, weight, and sitting heart rate, which are easily obtained in the field.

1.1 Statement of Purpose

Therefore, it is the aim of this study to quantify the relationship between physical activity level, as estimated by Rennie et al. (2001) using minute-by-minute heart rate monitoring, and estimates of cumulative low back loads estimated from video records of non-occupational activities. The establishment of a sufficiently strong relationship between heart rate determined physical activity level (HR-PAL) and cumulative low back loads, would possibly reduce the need for video documentation in future biomechanical analyses, making it possible for cumulative load assessment to be conducted over longer periods of time, at a much reduced cost.

1.2 Statement of Hypotheses

1. HR-PAL will account for a significant amount of variance in all seven cumulative L4/L5 spinal loads (compression, anterior and posterior joint shear forces, anterior and posterior reaction shear forces, and right and left mediolateral reaction shear forces) and six cumulative L4/L5 moments (extension and flexion moments, right and left lateral bend moments, and right and left axial twist moments).
2. There will be no differences between actual loads (estimated by video) and predicted loads (from HR-PAL equations) for any of the cumulative L4/L5 spinal loads (compression, anterior and posterior joint shear forces, anterior and posterior reaction shear forces, and right and left mediolateral reaction shear forces) and cumulative L4/L5 moments (extension and flexion moments, right and left lateral bend moments, and right and left axial twist moments).

If more physically active individuals experience a broader range of postures and loading situations than sedentary individuals, and since energy expenditure is related to physical activity level, then the level of energy expenditure during non-occupational activities is likely to be related to the associated cumulative loads. The shape of this relationship across all levels of physical activity is not known at present. This study will consider the relationship between cumulative low back loads and HR-PAL across a range of activities with low to moderate associated energy requirements.

Chapter II
Review of Literature

Exposure to risks for injury in the workplace has traditionally been a primary focus of biomechanical analyses of the low back. Previously, peak or instantaneous joint loading forces (such as spine compression forces) have been used to predict the risk of reporting low back pain (LBP). Although tolerance limit values for peak loading have been established (e.g. Snook & Ciriello, 1991; NIOSH: Waters et al., 1993) low back problems continue to represent a significant portion of compensable work injuries. In 2000, the Workplace Safety and Insurance Board of Ontario reported 29.3% of allowed lost-time claims in Ontario were due to back injuries, 19% of which were located in the lower back (i.e. lumbar, sacral, and coccygeal regions). Between 1998 and 2000, injuries involving the back (including the spine and spinal cord) accounted for 27% of all accepted time-loss injuries in Canada (Association of Worker's Compensation Boards of Canada (AWCBC), 2001).

2.1 Cumulative Spine Loading

The integration of the instantaneous loads on the low back (i.e. the cumulative load over an entire shift or day) has recently been identified as a significant risk factor for reporting low back pain. Kumar (1990) compared cumulative low back loads in institutional aides to the prevalence of back pain, and found significantly higher cumulative spine compression and shear forces in aides with pain, than in those without pain. Norman et al. (1998) compared cumulative vs. peak loads as a risk factor for reporting LBP, and found high correlations within peak and cumulative spinal loading variables, respectively, but low correlations between them. They concluded that cumulative spinal loads provide information that is different from peak spinal load in distinguishing those that reported pain from those that did not. Kerr et al. (2001) also found cumulative lumbar disc compression to be a robust risk factor for LBP, with significantly higher exposure levels among cases vs. controls. Jager et al. (2000) documented various measures of cumulative lumbar load (i.e. flexion and torsional moments, joint compression and shear forces) throughout an entire work shift (average shift length = approx. 4.74 hours). Based on the assumption that greater lumbar disc damage results from short exposures to high force amplitudes than from prolonged exposure to lower force amplitudes (Brinckmann et al., 1988), Jager et al. (2000) subjected the time courses for compressive force to a variety of force weightings (e.g. squared, raised to the power of four) and their respective exposure durations. While no specific recommendation was made as to which force weighting should be used, they concluded compression forces should be considered with a heavier weighting than exposure duration, due to the overload effect of high forces.

These studies indicate that reducing the magnitude of the peak loads on the low back may not be enough to reduce the risk of LBP. If cumulative loads are simultaneously increased, the risk of LBP may still be present. Daynard et al. (2001) confirmed this in a study of peak and cumulative spinal loads in health care workers during patient-handling activities. Although the use of assistive patient transfer equipment reduced the magnitude of peak spinal loads, they also required awkward trunk postures to be sustained for longer durations. The use of assistive devices was associated with significantly greater cumulative spinal loads than were transfers executed manually.

2.2 Collecting and Processing Cumulative Load Data

In spite of the evidence that cumulative spinal loading is a significant risk factor for reporting LBP, current methods of collecting and processing cumulative loading data are expensive and time consuming. The current criterion method for collecting and processing cumulative load data involves collecting video at 30 Hz, video digitization, and rectangular integration of resultant biomechanical outputs for the entire loading cycle (Callaghan et al., 2001). Efforts have been made to reduce the labour-intensiveness of collecting and processing cumulative loading data. Callaghan et al. (2001) compared five commonly used cumulative loading quantification methods to the criterion method, and determined that reducing the number of frames of data processed from 30 Hz to 5 Hz did not induce significant error into the cumulative loading estimates of symmetrical tasks. Andrews and Callaghan (2003) found further reducing the frames of data processed to 3 Hz did not induce greater than 5% error (relative to error at 60 Hz) in the majority of cases.

Assessment of cumulative loads requires long periods of subject observation, in order to obtain a representative sample of their activities throughout a shift or day. Keyserling (1986) investigated the reliability of a posture sampling approach in simulated real time. His method showed good agreement with another posture sampling approach, as well as good intraanalyst reliability. However, the results were less consistent between analysts, due to difficulty in classifying postures near the boundaries of adjacent posture categories. Keyserling (1986) concluded that inter-analyst reliability could be enhanced with improved training procedures. Neumann et al. (2001) investigated the use of a posture and load sampling approach to determine the risk of low back pain in occupational settings. Inter-observer reliability was tested on 10 jobs, 7 production jobs with regular cycles, and 3 non-production jobs with no regular cycle of activity. They found good inter-observer reliability for measurement of the percent time spent in flexed postures and twisted or laterally bent postures (ICC = 0.69 and 0.66, respectively). They also found excellent reliability for percent of time spent in neutral or severely flexed postures and for both peak and average spinal compression (ICCs between 0.82-0.92). At the group level, the posture sampling method employed by Neumann et al. (2001) was able to distinguish important risk factors for reporting LBP. Their results compared favourably to those achieved by Norman et al (1998) through video digitization.

2.2.1 Self-Report

Collection of cumulative load data would be greatly facilitated if it were possible to eliminate the need for video documentation. One method that would eliminate the use of video is the self-report questionnaire. Self-report measures enable researchers to collect a large amount of data at a low cost (Winkel & Westgaard, 1992); however, the validity and reliability of self-report measures are typically low. Burdorf and Laan (1991) evaluated the agreement between three methods for assessing postural loading of the low back. Exposure to strenuous back postures and movements were simultaneously assessed using a questionnaire, a self-administered log, and an observational method. These authors found large standard deviations for all postures and movements regardless of the method of assessment, and age-adjusted regression analysis revealed the proportion of variance explained by the questionnaire method was low for each parameter investigated. Burdorf and Laan (1991) concluded that the reliability of self-report methods is probably not very high. Van der Beek et al. (1994) compared self-reported estimates of exposure to tasks, activities, and postures of the trunk from a diary to observations of a whole working day. Their results revealed poor agreement and moderate correlation between self-reported and observed exposure. Two versions of the diary were used, an extensive version and a shortened version. The shortened version of the diary showed better agreement than the extensive version, but yielded less accurate exposure data. Van der Beek et al. (1994) concluded that self-report exposure data couldn't validly replace more objective measures of exposure assessment. Andrews et al. (1997) compared observed and self-reported peak low-back loads to loads obtained through video analysis. They found low correlations (0.4 or less) between the video and self-report methods for each load variable. Although higher correlations were found with the observational method (0.6 or greater), this method was only able to account for 36-64% of the variance relative to the video.

For self-report methods to be used in cumulative load analyses, subjects must report the frequency and duration of the tasks they perform, as well as the magnitude of the loads they handle and the various postures assumed throughout a task or day. Several studies have highlighted the poor precision (i.e. degree of over- or under-estimation) achieved with self-reported estimates of frequency and duration. Petersson et al. (2000) investigated the accuracy of self-rating of duration and frequency of lifting and sorting tasks under controlled laboratory conditions. In general, the duration was overestimated, while the number of repetitions was underestimated. Accuracy was lowest for short task durations, and repeated ratings of the number of repetitions throughout the day (rather than one rating for the whole day) did not increase the accuracy. Akesson et al. (2001) compared self-reported estimates of total daily exposure to vibration in dental hygienists to time-recorded measurements. Duration of exposure was self-estimated via diary and interview methods. On average, duration of exposure was overestimated 3 times more with the diary, and 8 times more in the interview, in comparison to time-recorded measurements.

Other studies have shown that while subjects' abilities to report exposure to work postures and handling of loads on a dichotomous level (i.e. exposed/not exposed) seems to be acceptable, their ability to quantify the exposures in greater detail is poor. Wiktorin et al. (1993) investigated subjects' ability to classify exposure to work postures and manual materials handling by means of a questionnaire. Four of the questionnaire items were validated with direct simultaneous measurements (i.e. pedometer, posiometer, and inclinometer); the remaining items were validated with an observation method. Agreement was tested at a dichotomous level for each of the 17 questionnaire items, and 5 items also tested frequency and duration on 4- and 6-point scales, respectively. Nine of the 17 questionnaire items showed acceptable agreement when tested at a dichotomous level (kappa 0.17-0.56), but the ability to quantify frequency and duration in greater detail was poor for all 5 items on which this ability was tested (kappa 0.06-0.35). Campbell et al. (1997) evaluated the repeatability of self-reports of occupational activities by workers doing the same job, as well as the agreement of these reports with findings from direct observation. Seven questionnaire items relating to work postures were classified dichotomously, and four items relating to frequency and magnitude of manual materials handling were classified on a 4-point ordinal scale. Generally, good agreement was found between workers (>90%) and with direct observation on items relating to working postures, i.e. dichotomous questionnaire items. The questionnaire appeared to reliably distinguish whether lifting masses in excess of 10 kg occurred. However, there was less agreement when reporting lifting above higher mass thresholds, and reports on the frequency of heavy lifting were inconsistent. Campbell et al. (1997) concluded that while questionnaires may be of use in highlighting major differences in physical demands across a range of jobs, they are unlikely to be of value in detailed quantification of physical demands.

2.2.2 Trunk Kinematics

Clearly, there is a need for a more objective means of quantifying loads on the low back. Agnew et al. (2002) investigated the use of an electromagnetic tracking device using only 4 sensors to obtain positional data in real time. They found the cumulative load estimates obtained with these devices did not significantly differ from estimates obtained through traditional video digitization methods. These devices could be used for gathering positional data in a laboratory setting with much less time spent in analysis. However, this method has not been validated for use in the field, and its ability to quantify loading during non-repetitive activity is not known.

The lumbar motion monitor (Marras et al., 1992) is a device used to directly quantify kinematic data on the lumbar spine in three dimensions. A triaxial electrogoniometer is attached directly in line with the subjects' spine, and essentially acts as an exoskeleton to the thoracolumbar spine (approximately T7-S2). The electrogoniometer is anchored to the thorax and the pelvis, and captures the instantaneous position, velocity, and acceleration of the trunk relative to the pelvis throughout a task.

The lumbar motion monitor (LMM) has been shown to be very reliable and accurate. Marras et al. (1992) investigated the ability of the LMM to accurately and reliably estimate range of motion (ROM), angular velocity, and angular acceleration. Estimates of these three measures were tested in the frontal, sagittal, and transverse planes. Flexion in the frontal and sagittal planes were tested at three ranges of motion (15, 30, and 45 degrees), and with three degrees of asymmetry (0, 15, and 30 degrees). Flexion in the transverse plane was tested at 14 and 28 degrees ROM, and zero degrees of asymmetry. The estimates from the LMM were compared to estimates measured simultaneously using a video-based, 2-dimensional motion analysis system (MA). ROM estimates using the LMM were found to be highly reproducible, with standard deviations ranging from 0.03 to 0.90 across all planes, ranges of motion, and degrees of asymmetry. Relative position error of the LMM was approximately half of that of MA, and angular velocity and acceleration estimates were at least as good as MA. Gill and Callaghan (1996) performed tests of intra- and inter-tester reproducibility under natural (i.e. unrestricted) motion conditions on the LMM. In general, they found good reproducibility, especially for estimates of ROM and angular velocity. Inter-tester reproducibility coefficients ranged from 0.93 to 0.98 across all measures and planes. Intra-tester reproducibility coefficients ranged from 0.82-0.87 for ROM, 0.61-0.87 for velocity, and 0.46-0.72 for acceleration.

The LMM shows great promise for use in cumulative load assessment. The LMM records the position of the thoracolumbar spine as a function of time. The postural information recorded with LMM can be used along with load moment information in a quantitative biomechanical assessment of the compression and shear forces acting on the lumbar spine (Marras et al., 1992). However, video documentation is still required to record the position of the hands. Also, the signals from the electrogoniometer must be downloaded directly into a computer. Even if long cables were used, this would seriously hinder subjects' ability to move freely throughout their homes, and limit the activities they would be able to carry out. This, in addition to the significant cost of the LMM unit, prohibits the use of the LMM in field studies of non-occupational tasks.

2.3 Cumulative Loading in Non-occupational Settings

Consideration of cumulative loads in conjunction with peak loads is likely to improve our ability to predict those at risk of reporting LBP. However, much of the research into cumulative loading has been performed on occupational tasks, with very little having been performed on activities in non-occupational settings. Milburn and Barrett (1999) investigated the static and dynamic peak spinal compression associated with making a bed, and found dynamic spine loads in excess of 6 kN. Lauder et al. (2002) quantified both peak and cumulative loads during simulated non-work activities. No subject exceeded the NIOSH Action Limit of peak load 3400 N (Waters et al., 1993) for any task, and cumulative compressive loads ranged from 2.2 kN·s (5 s quiet standing) to 17.9 kN·s (combination lift/folding clothes). In a subsequent study, Lauder and Andrews (2002) documented the magnitude of cumulative spinal loads associated with tasks commonly performed in non-occupational settings (e.g. vacuuming, mopping floors, folding clothes). They reported a mean cumulative compression on the lumbar spine of 10.08 (± 6.1) MN·s, for a 2-hour period. Azar et al. (2003) examined the accuracy of cumulative low back loads estimated from self-reported frequency and duration information during simulated, non-occupational tasks. They reported a mean cumulative compression of 6.56 (± 1.2) MN.s during simulated tasks similar to those performed by the subjects of Lauder and Andrews (2002), over a 2-hour period. By comparison, Norman et al. (1998)

documented cumulative compression over an entire shift, and found mean cumulative compressions of 21.0 MN·s (in those who reported LBP) and 19.5 MN·s (in those who did not report LBP). So, after only two hours of performing non-occupational tasks (Azar et al., 2003, Lauder and Andrews, 2002), subjects incurred approximately 30-50% of the cumulative compression sustained by subjects working in a large automotive assembly facility after an entire shift (Norman et al., 1998). The method used by Norman et al. (1998) to calculate the cumulative spine loads, has been shown to overestimate cumulative loads by approximately 70% (Callaghan et al., 2001). Thus, if it were assumed that the loads reported by Norman et al. (1998) are overestimated by 70%, after two hours of performing non-occupational tasks, subjects would have incurred approximately 98%-160% of the cumulative compression sustained by subjects working in a large automotive assembly facility after an entire shift. It is difficult to assess the degree of risk associated with the cumulative loads found by Lauder et al. (2002), Lauder and Andrews (2002), and Azar et al. (2003), since there are currently no tolerance limits in place for exposure to cumulative loads. However, the findings of Milburn and Barrett (1999), Lauder et al. (2002), Lauder and Andrews (2002), and Azar et al. (2003) clearly demonstrate significant spinal loads are being incurred while performing non-occupational tasks, and further investigation is warranted.

2.4 Data Collection in Non-Occupational Settings

In spite of recent success in reducing the labour-intensiveness of processing cumulative load data, the time-cost of collecting such data remains considerable. Because people tend to perform home activities randomly, and the majority of the tasks are non-repetitive in nature, a minimum data collection time of several hours need to be undertaken in order to obtain a representative sample of the activities subjects perform throughout an entire day. Potential subjects might be less willing to participate in studies involving lengthy data collections. Moreover, the entire two hours must be videotaped to obtain accurate documentation of the tasks performed by the subject.

Video documentation creates a multitude of problems. Impression management theory states that people will try to present themselves in the best light possible (Sternberg, 1995). People engage in impression management to influence how others think of them, usually because they want to make a positive impression (Weiten and Lloyd, 1997). Being physically active is perceived as a socially desirable behaviour, while being lazy is not. Thus, a subject who would normally watch two (or more) hours of television in a given afternoon will find less passive activities to engage in while under observation. This has implications for cumulative loading, because the activities they engage in while under observation may not be representative of their typical routine, resulting in an overestimation of their usual cumulative load. Potential subjects may also perceive the videotaping of activities within their homes as invasive, and be less willing to participate. Finally, if the video data are to be used for digitization and biomechanical modeling, videotaping must take place at an angle to the subject that affords a clear view of the subject at all times (e.g. sagittal view). This can be a problem, because every subject's house is different, and room sizes and layouts are variable.

2.5 Physical Activity

There is a need for an objective means of quantifying exposure to risk factors for reporting LBP, without the associated costs presented by traditional video assessment. Determining the level of physical activity may provide such a method. The energy requirements of individuals who are more physically active will be greater than those of their more sedentary counterparts. Presumably, more active individuals will move through a greater range of postures and handle a greater number of loads, thereby undergoing a greater exposure to cumulative load than more sedentary individuals. Therefore, a person's level of energy expenditure during non-occupational activities may provide an indication of the cumulative spine loads sustained during the same activities.

2.5.1 Doubly Labeled Water

Several methodologies exist for evaluating level of physical activity or energy expenditure, including doubly labeled water (Schoeller, 1988), self-report, mechanical and electronic motion detectors, cardio-respiratory fitness, and heart rate monitoring. The doubly labeled water method (DLW) is currently considered the criterion method for measuring energy expenditure in free-living conditions. DLW is based on the assumption that, after an oral dose of $2H_218O$, $2H_2$ is eliminated from the body as water, while 18O is eliminated as both water and exhaled carbon dioxide (Ebine et al., 2002). 2H and 18O leave the body at different rates, and the difference in the loss rates is proportional to the rate of carbon dioxide (CO_2) production (Stein et al., 1987). Energy expenditure can then be calculated from the rate of production of CO_2.

The advantages with DLW include its ease of administration and its suitability for field studies (Stein et al., 1987). As a method of data collection, it is also relatively non-invasive and causes minimal interference with the subject's daily routine (Ebine et al., 2002). However, DLW is quite costly. In 1988 the cost of a single dose was $300 USD (Schoeller, 1988). In addition, due to an increased sensitivity to errors over shorter measurement periods (Stein et al., 1987), DLW can only provide information about energy expenditure over a period of 1-3 weeks (Philippaerts et al., 1999, 2001). A cost-effective method that can determine energy expenditure over much shorter periods of time (i.e. 2 hours or 1 day) is attractive for use in biomechanical assessments.

2.5.2 Self-Report

2.5.2.1 Recall Bias

While DLW may be the criterion method, self-report methods such as questionnaires and activity diaries are the most widely used methods of physical activity assessment. Their ease of administration, cost-effectiveness, minimal invasiveness, and minimal subject time and commitment make them a popular choice in larger-scale studies (Staten et al., 2001). However, in addition to the previous discussion of the limitations of self-reports (see section 2.4.2), a potential confound lies in subjects' abilities to recall moderate and light intensity activity. Several studies have shown that subjects have more difficulty recalling bouts of less structured moderate- and light-intensity activity than more high-intensity bouts of structured exercise. In an investigation of the ability of children and adolescents to recall activities of varying degrees of intensity, Sallis et al. (1993) found subjects were able to accurately recall hard and very hard activities, but could not do so for moderate activities. This effect is not limited to children and young adults. Dipietro et al. (1993) sought to establish the reliability and validity of a questionnaire to assess physical activity among older adults, namely, the Yale Physical Activity Survey (YPAS). They found that high-intensity exercise-related activities were more reliably reported than less structured, lower-intensity activities. They were also unable to establish validity for several of the questionnaire items designed to assess low intensity activity. Under reporting of low- and moderate-intensity activities will result in an overestimation of energy expenditure.

2.5.2.2 Questionnaire Validation

Another problem with self-report questionnaires is that until recently, there has been no criterion method for questionnaire validation. Criterions against which questionnaires have been validated include DLW, accelerometers and/or motion sensors, oxygen consumption (VO_2), body fatness, body-mass index, muscular endurance, physical work capacity, fitness profile, and heart rate-VO_2 relationship. DLW is now largely considered to be the criterion against which activity questionnaires should be validated, and several questionnaires have been successfully validated in this fashion (Schuit et al., 1997, Philippaerts et al., 1999, Staten et al., 2001). In spite of this, the use of DLW as a criterion may prohibit their use in biomechanical analyses. As previously discussed (section

2.5.1), DLW can only provide information on the average total daily energy expenditure over a period of 1-3 weeks. Typically, biomechanical analyses of cumulative spine loading take place over a matter of hours. Thus, if estimates of physical activity are to be used in biomechanical analyses, questionnaires validated against DLW cannot be used because they have not been validated for use over such a short period of time.

2.5.3 Accelerometers

Accelerometers are typically worn at the waist, and record vertical accelerations of the body during movement. The acceleration counts are used in conjunction with age, sex, height, and weight to estimate the energy expended during a task or day (Maliszewski et al., 1991). The advantages of accelerometers are they are small, lightweight, easy to use, and provide objective measures of activity. They also feature interval-based time sampling and computer download capabilities, making them well suited for field based research (Welk et al., 2000). A disadvantage of waist-mounted accelerometers is that they do not detect arm movements, which results in an underestimation of energy expenditure during activities that are primarily performed with the upper limbs, such as sweeping floors and putting away groceries. The addition of an arm accelerometer does not greatly improve the estimate of energy expenditure. Swartz et al. (2000) found that the addition of an arm-mounted accelerometer was only able to account for an additional 2.6% of the variance in estimated energy expenditure over the waist-mounted accelerometer alone. They concluded that the small improvement in the estimate is offset by the time required to analyze the data and the cost of the accelerometer.

Accelerometers cannot account for the additional metabolic cost associated with activities performed under load-bearing conditions, such as carrying a small child or backpacking. Similarly, accelerometers will not detect an increase in energy expenditure due to walking/running on graded terrain or walking up stairs. A study by Montoye et al. (1983) compared accelerometer readings to estimates of energy expenditure from indirect calorimetry (VO_2) for subjects walking at 0, 6, and 12% grades, and running at 0 and 6% grades. As expected, the accelerometer did not reflect the increased energy costs when the grade was increased during walking or running.

Uniaxial accelerometers only record accelerations in the vertical direction. This will result in an underestimation of energy expenditure during activities in which these movements do not occur or occur very little, such as bicycling and ice-skating. In an effort to counteract this effect, triaxial accelerometers have been used, which measure accelerations in three orthogonal planes. Bouten et al. (1994) investigated the ability of a triaxial accelerometer to quantify energy expenditure during sedentary activities and walking under controlled laboratory conditions. The integral of the absolute value of the accelerometer output (IAA_{tot}) was significantly correlated with energy expenditure due to physical activity (EE_{act}), for the pooled data of all subjects and activities ($r = 0.95$, $p<0.001$). However, the commercially available triaxial accelerometer, the Tritrac-R3D (Professional Products Reining Int., Madison, WI) has been shown to underestimate physical activity related energy expenditure under free-living conditions by 35% in comparison to doubly labeled water (Leenders et al., 2001). Thus, the reliability and validity of the Tritrac for use in field studies remains in question.

2.5.4 Heart Rate Determined Physical Activity Level

In the present study, minute-by-minute heart rate (HR) monitoring is proposed as a method of quantifying energy expenditure (EE), and therefore physical activity level (PAL). Strath et al. (2000) demonstrated that heart rate is a strong predictor of EE during moderate physical activity, after adjusting for age and fitness level (r=0.87, *SEE*=0.76 MET). With physical activity, the body's demand for oxygen is increased, which in turn leads to an increase in the rate of ventilation, or breathing. Heart rate and stroke volume increase, in order to transport oxygen to the muscles more quickly. Water and carbon dioxide (CO_2) are the bi-products of the body's consumption of oxygen. CO_2 is returned to the lungs via the bloodstream for expiration, and the volume of expired CO_2 is proportional to energy expenditure. Heart rate is proportional to rate of ventilation, and therefore also reflects EE.

It is widely assumed that there is a linear relationship between heart rate (HR) and oxygen consumption (VO_2). However, this assumption does not hold at energy expenditure levels approaching rest. Spurr et al. (1988) developed a method of compensating for the non-linearity of the HR-VO_2 relationship at low activity levels, called the HRFlex method. With this method, the HRFlex, or flex point, is calculated as the average of the highest HR achieved during rest and the lowest HR achieved during activity. This point represents the heart rate at which the assumption of linearity no longer holds (Rennie et al., 2001). Below this point, EE is assumed to equal the resting energy expenditure (REE). Above it, EE is estimated from the slope and the intercept of the calibration curve obtained during activity (Spurr et al., 1988). Estimates of EE by this method have been found to correlate well with whole body calorimetry ($r = 0.87$: Spurr et al., 1988; $r = 0.94$: Ceesay et al., 1989), as well as with doubly labeled water (% difference = 2.0 ± 17.9 MJ/d: Livingstone et al., 1990).

The use of the relationship between HR and VO_2 to quantify EE has been impractical for large-scale studies, because of the need to establish individual regression lines from laboratory measurements (Hiilloskorpi et al., 1999). Rennie et al. (2001) developed a method of estimating EE and PAL from minute-by-minute heart rate monitoring, without the need for individual calibration. The standard HRFlex method is based on four parameters: resting energy expenditure (REE), the slope and the intercept of the regression line between EE and HR during exercise, and the HRFlex point (Rennie et al., 2001). Rennie et al. (2001) developed prediction equations for each of these parameters, based on measurements that are easily obtained in the field, such as mass, age, and body fat percentage. Regression analysis revealed the following prediction variables as significant: age (years), sex, mass (kg), body mass index (kg/m^2), and sitting pulse rate. Slope and intercept (the parameters of the regression line) could not be tested independently, because they are highly correlated. The predicted slope produced a higher adjusted R^2 than the predicted intercept (R^2 =

0.34 and R^2 = 0.32, respectively), and was therefore chosen for use in the final prediction model. The intercept is anchored at zero. Equations (1) through (3), provided by Rennie et al., (2001), are as follows:

REE = -1.1(sex{1,2}) + 0.04(weight) + 0.02(sitting pulse rate) **(1)**

HRFlex = 1.7(sex{1,2}) + 0.23(BMI) + 0.93(sitting pulse rate) **(2)**

Slope = -0.12(sex{1,2}) + 0.002(age) + 0.003(weight) **(3)**

The sex variable is a coded variable, where a value of 1 represents a male, and a value of 2, a female. Figure 3 depicts a sample calibration curve. The study

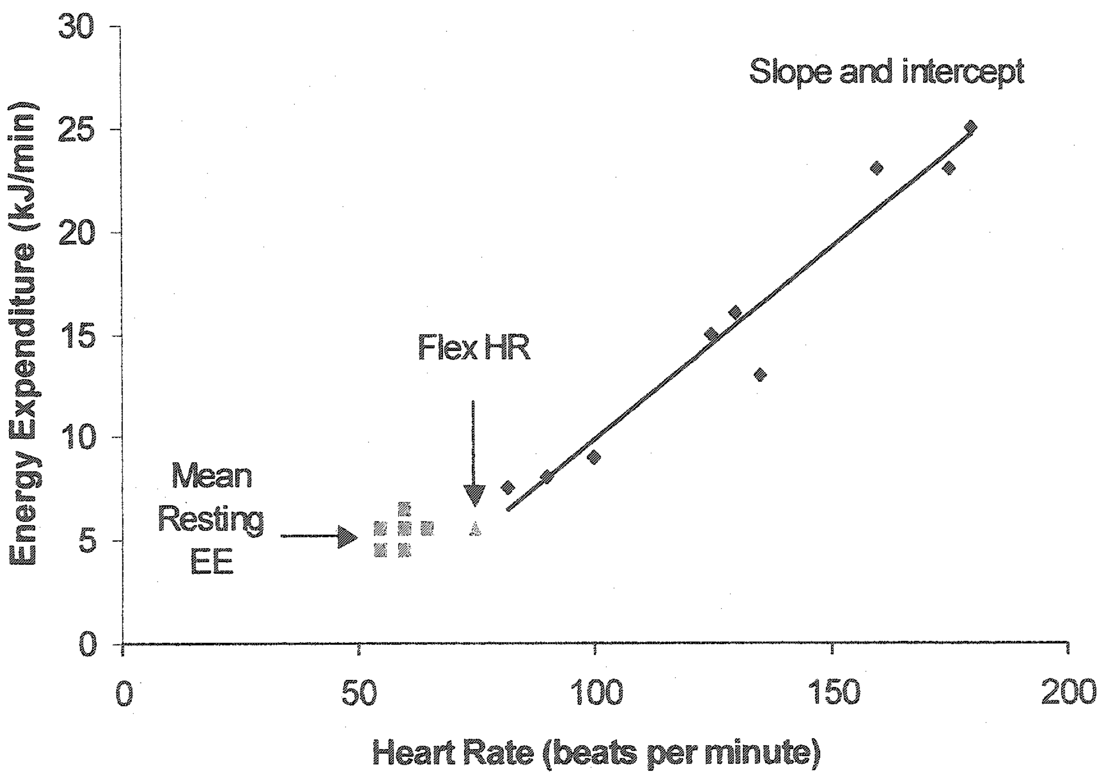

Figure 3: Sample HR-VO_2 Calibration Curve (Adapted from Rennie et al., 2001). Once REE, HRFlex, and slope have been predicted, the instantaneous EE (kJ/min) can be estimated for every collected HR value. If the HR data point is less than the predicted HRFlex, EE is assumed to equal the predicted REE. Otherwise, it is estimated using the predicted slope and an intercept of zero.

sample used to derive the calibration parameter predictions consisted of 789 Caucasian subjects, and an independent sample of 97 subjects was used to test the validity of the parameter predictions. Correlations between observed and estimated calibrations were: $r = 0.73$ ($p<0.001$) for resting energy expenditure, $r = 0.93$ ($p<0.001$) for HRFlex, and $r = 0.76$ ($p<0.01$) for slope.

Once REE, HRFlex, and slope have been predicted, the instantaneous EE (kJ/min) can be estimated for every collected HR value. If the HR data point is less than the predicted HRFlex, EE is assumed to equal the predicted REE. Otherwise, it is estimated using the predicted slope and an intercept of zero. Total EE (TEE) is calculated by multiplying the average of the instantaneous EEs by the duration of the activity in minutes. Physical activity level (PAL) is taken as the ratio of TEE to REE.

The advantages of using heart rate determined physical activity level (HR-PAL) are that the method is objective, non-invasive, and relatively inexpensive. Heart rate also reflects changes in the intensity of activities, unlike accelerometers. Heart rate monitors are capable of sampling at regular intervals and storing information for long periods. The information can then be downloaded into a computer through a serial interface. The validity and reliability of HR monitors using chest electrodes, such as the Polar HR monitors (Polar Electro Inc., Port Washington, New York), to be used in the present study, have long since been established (Karvonen et al., 1984; Leger and Thivierge, 1988; Treiber et al., 1989).

A potential problem with HR-PAL is that heart rate is influenced by several external factors, including emotion, posture, use of stimulants (caffeine, nicotine) or depressants (alcohol), altitude, and climate (Haskell et al., 1993; Hiilloskorpi et al., 1999; Rennie et al., 2001). Taking a baseline heart rate measurement immediately prior to initiating data collection will reduce the influence of these factors. Another potential problem is that the relationship between HR and VO_2 differs between subjects depending on their level of physical fitness. Highly trained individuals will exhibit a lower HR for a given value of VO_2. Type of activity may also affect the relationship between HR and VO_2. Haskell et al. (1993) demonstrated that VO_2 is lower at a given heart rate for activities performed primarily with the arms (arm ergometer) than for activities performed primarily with the legs (treadmill walking). The coefficients derived by Rennie et al. (2001) to predict the slope of the line were developed on subjects pedaling on a cycle ergometer. However, many non-occupational activities involve a combination of arm and leg activity, and results from Haskell et al. (1993) also indicated that the HR-VO_2 relationship for activities of this type is very similar to that for leg exercise.

2.6 Summary

Consideration of cumulative spine loading during non-occupational activities is likely to contribute to our understanding of the risk of reporting LBP. Current video-based methods of quantifying cumulative spine loads are time-consuming, invasive to subjects, and costly. Non-video methods such as self-report questionnaires are not sufficiently accurate or reliable for use in biomechanical analyses. The need for an objective, cost-effective, and reliable method of data collection has lead to the consideration of a potential relationship between individuals' levels of energy expenditure during non-occupational activities, and their associated cumulative load. Heart rate monitoring is known to be a reliable method for assessing energy expenditure, and recent work by Rennie et al. (2001) has eliminated the need for individual HR/VO_2 calibration curves. The aim of the current research is to explore the relationship between HR-PAL as estimated by Rennie et al. (2001) and estimates of cumulative loads (calculated through traditional video assessment) during non-occupational activities performed over the same measurement period. Establishment of a sufficiently strong relationship might reduce the need for video documentation in future biomechanical analyses, making it possible for cumulative load assessment to be conducted over longer periods of time, at a greatly reduced cost.

Chapter III
Methodology

3.1 Subjects

A total of 14 subjects (7 male, 7 female) were recruited from the faculty population at the University of Windsor, as well as from the general population of Windsor and Essex County and the Kitchener-Waterloo area. Ten subjects (5 male, 5 female) made up a regression equations generation sample (mean age = 47.3 ± 9.1 years, mean mass = 76.7 ± 16.2 kg, mean height = 1.7 ± 0.1 m); the remaining 4 subjects formed a validation sub-sample (mean age = 48.8 ± 3.5 years, mean mass = 80.5 ± 21.1 kg, mean height = 1.7 ± 0.1). Subjects ranged in age between 36 and 61 years. This age range was chosen in order to closely match the age range of the subjects used by Rennie et al. (2001) to develop the HR-PAL prediction equations used in the present study. All subjects were free from any back pain at the time of the study. Prior to participation in this study, each subject read and signed an informed consent form approved by the Research Ethics Board of the University of Windsor. Ethics approval and consent forms are presented in Appendices A and B, respectively.

3.2 Data Collection

A flow-chart depicting the steps taken during data collection and analysis can be found in Appendix C. Data collection took place over approximately three hours at each subject's residence. Participants were first given background information about the study, and were asked to review and sign the informed consent form. Their height and mass were measured, and recorded along with their age and gender. The subjects were outfitted with a Polar Accurex Plus heart rate monitor (Polar Electro Inc., Port Washington, New York), which recorded the subject's heart rate (HR) at five-second intervals throughout the 2-hour data collection. Before data collection began, sitting HR was established. The monitor recorded their HR at five-second intervals over five minutes, while the subjects sat quietly in a chair.

Once sitting HR was collected the subjects were instructed to go about their normal daily routine, performing both active and/or quiet activities that they would normally do on any other given day. As such, the researcher did not predetermine the tasks to be performed by the subjects. The subjects were continuously recorded by video for a period of two hours. To assure participants felt at ease in the presence of the researchers and video camera, an adjustment period of ten minutes was included at the beginning of each session. The subject was instructed to begin their usual routine with the initiation of the heart rate collection, but the investigators only pretended to turn on the camera and start videotaping. This allowed the subject to settle into their routine and alleviate any nervousness they may have had prior to initiating true data collection. The first ten minutes of heart rate collection were not used in any subsequent data analyses.

Before data collection began, the investigators asked the subjects to give them an idea of the activities they might be doing during the session. This afforded the investigators the opportunity to view the rooms in which the subjects were to be working, allowing them to anticipate the subjects' movements and plan their positioning to obtain the best possible camera angle during filming.

Due to equipment limitations, the subjects were restricted to performing tasks within their own homes or on their own properties. Also, subjects were not permitted to use electrical appliances with small, high-amp motors (i.e. vacuums, dust-busters, etc). These appliances create static electricity, which interferes with the signal transmission from the chest strap of the HR monitor to the receiver. Finally, due to limitations of the biomechanical model used in this study, subjects were only permitted to perform tasks that could be done in upright postures (i.e. sitting, standing, kneeling, etc). Tasks that must be performed in prone or supine positions, such as mechanical work on a vehicle, were not permitted. The subjects were informed of these restrictions before data collection began.

After the initial adjustment period, the video camera was turned on. The video and the HR data were synchronized using a trigger light placed in the camera's field of view. While one researcher operated the video camera, the other kept a written record of the type and mass of every load the subject handled. The loads were subsequently used for input into a biomechanical model to compute cumulative spine loads. Wherever possible, the view of the camera was midway between the sagittal and frontal planes, capturing the subject from the mid-thighs up on either the right- or left-hand side.

Throughout the session, the researchers made note of any obvious situations where room size or furniture placement made it difficult to clearly capture the task performed by the subject. At the end of the 2-hour collection, these tasks were recreated or "mocked-up", and the subject performed the recreated tasks for one minute per task. No HR data was collected during the recreation of tasks. Although the researchers were as vigilant as possible in making note of these situations as they arose, some instances where the camera angle was poor were not noticeable until the video document was analyzed. If the poorly captured task could not be represented by a similar task already captured in the first session, a second session to recreate the poorly captured tasks was required. Again, recreated tasks were performed for one minute each, and the subjects were not required to wear the HR monitor, as the HR collected during the actual task was used. The time requirement of the second session, when necessary, was approximately 30 minutes.

3.3 Heart Rate Data Processing

Heart rate data were downloaded into a computer through a serial interface (Polar Interface Plus, Polar Electro Oy, Kempele, Finland) and processed using Polar Training Advisor Software (Polar Electro Oy, Kempele, Finland). The first ten minutes of the HR profile was not used in subsequent analyses; this time period was used to allow the subject to settle into their routine and adjust to the presence of the investigators in their home. The last 10 minutes of the data collection were also excluded from further analysis, resulting in a total session time of approximately 100 minutes.

Sitting HR was taken as the median of the last three minutes of the five-minute collection period. Only the readings during the final 3 minutes were used, to allow HR to reach a steady state. The median, rather than the mean, sitting heart rate was chosen because outlying data points do not influence median values.

The HR profile, along with the subjects' height, mass, age, gender, and median sitting HR, were used as inputs into the regression-based mathematical model of Rennie et al. (2001) to estimate physical activity level (PAL). Equations (1) through (3), provided by Rennie et al., (2001), were used to calculate resting energy expenditure (REE), heart rate flex point (HRFlex), and the slope of the relationship between energy expenditure above rest and heart rate:

$$\text{REE} = -1.1(\text{sex}\{1,2\}) + 0.04(\text{weight}) + 0.02(\text{sitting pulse rate}) \quad (1)$$

$$\text{HRFlex} = 1.7(\text{sex}\{1,2\}) + 0.23(\text{BMI}) + 0.93(\text{sitting pulse rate}) \quad (2)$$

$$\text{Slope} = -0.12(\text{sex}\{1,2\}) + 0.002(\text{age}) + 0.003(\text{weight}) \quad (3)$$

Once REE, HRFlex, and slope were predicted, the instantaneous EE (kJ/min) was estimated for every minute of the data collection period. If the HR data point was less than the predicted HRFlex, EE was assumed to equal the predicted REE; otherwise, it was estimated using the predicted slope and an intercept of zero. Total EE (TEE) was calculated by multiplying the average of the instantaneous EEs by the duration of the activity in minutes. Physical activity level (PAL) was taken as the ratio of TEE to REE.

Occasionally, the leads from the monitor's chest strap came away from the subjects' body during movement, resulting in small gaps in the HR profile. These gaps were filled using the average of the HR data points on either side of the gap (Leonard et al., 1997). The same procedure was employed if more than one minute of data was affected, but if more than three successive minutes were lost the unusable portion of the subject's data were discarded. Significant portions of HR data were lost for three subjects in this study. While it was possible to re-collect the data for one of the subjects, this was not possible for the other two. The usable data collected for these subjects were extrapolated up to 100 minutes, so that all subjects would have equal data collection times.

3.4 Video Data Processing

The video data were captured to digital format at 3 Hz (Andrews and Callaghan, 2003) using Virtual Dub 1.4.13 software (Free Software Foundation). The video was trimmed to match the heart rate file, and each task was then trimmed out into separate video image clips using the Ariel Performance Assessment Software (ARIEL Technologies Inc.). The short video clips were subsequently analyzed with the 3-D Match video analysis tool (University of Waterloo, Waterloo, Ontario - section 3.5).

In order to reduce the labour-intensity of processing the video data, repetitive and recreated tasks, as well as tasks performed in standard postures with little movement and load bearing were represented by a short, "sample" video clip. For instance, washing dishes at a sink involves very little movement other than that of the upper limbs, and for the most part, very small hand loads (<1 kg). If a subject washes dishes for 10 minutes, rather than digitize the entire 10 minutes, a brief representative sample of the task can be digitized and modeled to yield the cumulative load for the representative task. This load can then be extrapolated to yield the cumulative load for the full 10-minute task.

3.5 3-D Biomechanical Modeling

Throughout the session, the magnitude of the loads handled by the subjects, and the peak push and pull forces, were measured with a digital force gauge. The loads and forces applied at the hands, along with the subjects' height, mass, and gender, were used as inputs into a quasi-static 3-dimensional biomechanical model (3-D Match, University of Waterloo, Waterloo, Ontario). The interface of 3-D Match employs a posture sampling method. The trimmed video clips were loaded into 3-D Match, and for each frame of video the investigator selected the postures of the trunk, neck, upper arm, and lower arm from the categorical scales provided in the model (Appendix D). The posture parameters and the number of posture choices for each parameter, for each body part are listed in Table 1. The subject's height and mass, as well as the loads in the hands (considered separately) are entered into 3-D Match for every frame. Tests of the intra-observer reliability of 3-D Match have shown the repeatability of posture selections within observers over three test days to be

Table 1: Posture Sampling Parameters for 3-D Match.

Body Part	Posture Parameter	# Of Categories
Trunk	Flexion/Extension	6
	Lateral Bend	3
	Rotation	3
Neck	Flexion/Extension	4
	Lateral Bend	2
Right/Left Arm	Flexion/Extension	6 per limb
	Abduction/Adduction	4 per limb
Right/Left Forearm	Flexion/Extension	3 per limb

excellent – the average percent agreement of the posture selections made on each day ranged from 83.68% to 99.05% (Jackson et al., 2003). Intraclass correlation coefficient analysis of cumulative loading variables indicated a lower repeatability of output variables (ranging from $ICC<0.4$ to $ICC>0.75$), although the highest *ICC*s were found for cumulative compression and anteroposterior reaction shear, measures that are commonly used in determining risk of exposure (Jackson et al., 2003).

Based on the positional data from the video, 3-D Match estimates spine compression at every frame using a third order, four-dimensional polynomial (Equation (4): McGill et al., 1996):

$$\begin{aligned} C = {} & 1067.6 + 1.219F + 0.083F^2 - 0.0001F^3 + 3.229B \\ & + 0.119B^2 - 0.0001B^3 + 0.862T + 0.393T^2 - 0.0001T^3 \end{aligned} \tag{4}$$

where C = compression (N), F = flexion-extension moment (Nm), B = lateral bending moment (Nm), and T = axial twisting moment (Nm). McGill et al. (1996) generated this equation using compression and three moments about a global axis at L4/L5, estimated from a 90 muscle anatomical model of the spine. Subjects performed a variety of tasks, which were captured by two synchronized video cameras placed at right angles to each other. The joint centers of the body segments were digitized from both video images, resulting in 3-D joint coordinates of the estimated joint centers. The joint coordinate data were input to a 3-D linked segment model to obtain the external forces and the three moments acting on the lumbar spine. Electromyography (EMG) was used to partition the internal moment necessary to oppose the external moment, caused by the hand held load and the upper body weight, between all 90 muscle fascicles. Seventy-five moment and compression combinations were subjected to a convergence algorithm, and the third order polynomial was chosen as the best compromise between the fit of the data and the biological feasibility of the polynomial.

3-D Match yielded estimates of the following cumulative output variables for every frame of data: lateral bend, flexion-extension, and axial twist moments (N·m); joint and reaction compression forces (N); anteroposterior (A/P) joint and reaction shear forces (N); mediolateral (M/L) reaction shear force (N); and the amount of flexion/extension, lateral bend, and axial twist in degrees. The model calculates cumulative loads for each task using rectangular integration of the force-time histories. The model output includes the cumulative loads for flexion, extension, right and left lateral bend, and right and left axial twist moments (N·m·s), compression force (N·s), joint and reaction anterior and posterior shear forces (N·s), and left and right reaction mediolateral shear forces (N·s). The model also includes in its output the peak values for all loading parameters; kinematic information of the spine (e.g. maximum and range of degrees of flexion) and time and percent of cycle spent in flexed, laterally bent, and axially twisted trunk postures. The focus of the present study is the cumulative loading outputs. The total cumulative load for the entire session was obtained by summing the cumulative loads from each task.

3.6 Statistical Analysis

Ten subjects (5 male and 5 female) formed a regression equation generation sample. Simple regression was used to derive equations for the relationship between heart rate determined physical activity level (HR-PAL) and cumulative load, for each cumulative output variable. Four additional subjects (2 male and 2 female) formed a validation sub-sample, to test the validity of the regression equations. Independent samples *t*-tests were used to ensure that the subjects in the generation and validation samples did not differ significantly with respect to age, mass, height, sitting HR, working HR, and HR-PAL. Predicted cumulative low back loads (from HR-PAL) and “actual” cumulative low back loads estimated from video were compared using paired samples *t*-tests, for each cumulative output variable. Paired samples correlations were used to assess the strength of association between predicted and actual loads, for each cumulative output variable. The root mean square (RMS) error was also computed. The significance of the associations was tested at alpha levels of 0.05 and 0.1. All statistical analyses were carried out using SPSS 11.0 software (Statistical Package for the Social Sciences, SPSS Inc, Chicago, IL).

Chapter IV
Results

4.1 Demographics

Means and standard deviations for subject demographic data are presented in Table 2. Independent samples *t*-tests showed no significant differences between the generation and validation samples with respect to age, mass, height, sitting heart rate, working heart rate, and heart rate determined physical activity level (HR-PAL). A summary of the mean loads (± *SD*) for all cumulative output variables across all subjects, and for the generation and validation samples, respectively, can be found in Table 3. No significant differences between the generation and validation samples were found, for any of the cumulative output variables.

Table 2: Subject Demographics. Mean (± SD) age, mass, height, resting heart rate, working heart rate, and HR-PAL for both generation and validation samples. No significant differences between the generation and validation samples were found, for any of the demographic variables

Variable	Generation Sample	Validation Sample	*t*	*p*
Age	47.3 (9.1)	48.8 (3.5)	-0.3	0.77
Mass	76.7 (16.2)	80.5 (21.1)	-0.36	0.72
Height	1.7 (0.1)	1.7 (0.1)	0.26	0.79
Resting Heart Rate	71 (14.1)	67.5 (20.5)	0.38	0.71
Working Heart Rate	89.3 (13.6)	87.2 (24.3)	0.21	0.84
HR-PAL	1.71 (0.72)	1.72 (0.41)	-0.08	0.94

Table 3: Cumulative Load Comparison. Mean (± SD) cumulative loads across all subjects (N = 14), and for the generation (N = 10) and validation (N = 4) samples. No significant differences between the generation and validation samples were found, for any of the cumulative output variables.

Cumulative Output Variable	All Subjects (N = 14) Mean (± SD)	Generation Sample (N = 10) Mean (± SD)	Validation Sample (N = 4) Mean (± SD)	t	p
Compression Force (MN.s)	8.31 (2.94)	9.37 (2.64)	6.05 (3.85)	-1.357	0.27
Joint Anterior Shear Force (kN.s)	163.17 (123.3)	224.10 (153.40)	70.64 (28.07)	-2.095	0.13
Joint Posterior Shear Force (kN.s)	79.46 (81.1)	70.87 (48.89)	122.98 (145.43)	0.588	0.60
Reaction Anterior Shear Force kN.s)	486.30 (359.1)	626.54 (461.29)	225.29 (154.15)	-1.637	0.20
Reaction Posterior Shear Force (kN.s)	19.44 (50.1)	9.13 (17.55)	53.05 (91.22)	0.885	0.44
Reaction Right ML Shear Force (kN.s)	19.39 (25.4)	29.40 (36.56)	13.41 (14.21)	-0.762	0.50
Reaction Left ML Shear Force (KN.s)	24.60 (32.2)	21.80 (24.72)	20.76 (38.49)	-0.045	0.97
Flexion Moment (kN.m.s)	249.39 (163.7)	303.29 (199.10)	145.88 (119.38)	-1.318	0.28
Extension Moment (kN.m.s)	1.72 (3.1)	1.50 (2.77)	2.69 (4.34)	0.394	0.72
Right Lateral Bend Moment (kN.m.s)	13.51 (11.9)	13.63 (7.90)	10.56 (15.28)	-0.361	0.74
Left Lateral Bend Moment (kN.m.s)	12.33 (13.0)	18.08 (18.18)	10.47 (8.50)	-0.655	0.56
Left Axial Twist Moment (kN.m.s)	5.65 (7.1)	5.10 (6.11)	10.49 (11.21)	0.703	0.53
Right Axial Twist Moment (kN.m.s)	4.80 (6.8)	4.30 (2.91)	8.41 (12.35)	0.715	0.53

4.2 Simple Regression

The quadratic regression of HR-PAL onto each of the cumulative output variables produced R^2 values ranging from R^2 = 0.078 for reaction left mediolateral (ML) shear force, to R^2 = 0.817 for compression force. At an alpha level of 0.05, the regression equations were able to account for a significant amount of variance in three of the 13 cumulative output variables: compression force (Fig. 4a), flexion moment (Fig 4b) and right axial twist (AT) moment (Fig. 4c). When an alpha level of 0.1 was used, the regression equations were able to account for a significant amount of variance in an additional four cumulative output variables: reaction anterior shear force (Fig. 4d), extension moment (Fig. 4e), left lateral bend moment (Fig. 4f), and left axial twist moment (Fig. 4g). A summary of all regression equations and their R^2, F, and p values are listed in Table 4. The non-significant relationships between HR-PAL and cumulative output variables are depicted in Appendix E.

Table 4: Regression Coefficients and Statistical Values. HR-PAL was able to account for a significant amount of variance in three cumulative output variables: cumulative compression force, cumulative flexion moment, and cumulative right axial twist moment. Boldface values are statistically significant at an alpha level of 0.05 (N = 10); italicized values are significant at an alpha level of 0.1 (N = 10).

Cumulative Output Variable	X^2	X	Intercept	R^2	F	p
Compression Force (MN.s)	-4.33	19.32	-9.14	***0.817***	***15.64***	***0.00***
Joint Anterior Shear Force (kN.s)	-195.48	833.86	-562.79	0.286	1.40	0.31
Joint Posterior Shear Force (kN.s)	-10.06	74.22	-30.68	0.465	3.05	0.11
Reaction Anterior Shear Force (kN.s)	-751.24	3246.66	-2413.30	*0.573*	*4.70*	*0.05*
Reaction Posterior Shear Force (kN.s)	-5.62	33.87	-32.83	0.447	2.83	0.13
Reaction Right ML Shear Force (kN.s)	-13.95	82.63	-72.13	0.452	2.88	0.12
Reaction Left ML Shear Force (kN.s)	-28.73	117.42	-77.22	0.078	0.30	0.75
Flexion Moment (kN.m.s)	-362.87	1588.60	-1195.00	***0.757***	***10.90***	***0.01***
Extension Moment (kN.m.s)	-2.97	14.19	-12.85	*0.492*	*3.39*	*0.09*
Right Lateral Bend Moment (kN.m.s)	-13.46	59.49	-41.39	0.257	1.21	0.35
Left Lateral Bend Moment (kN.m.s)	-9.39	52.26	-44.41	*0.535*	*4.02*	*0.07*
Left Axial Twist Moment (kN.m.s)	-1.64	10.55	-8.75	*0.492*	*3.39*	*0.09*
Right Axial Twist Moment (kN.m.s)	-5.20	23.39	-19.02	***0.769***	***11.66***	***0.01***

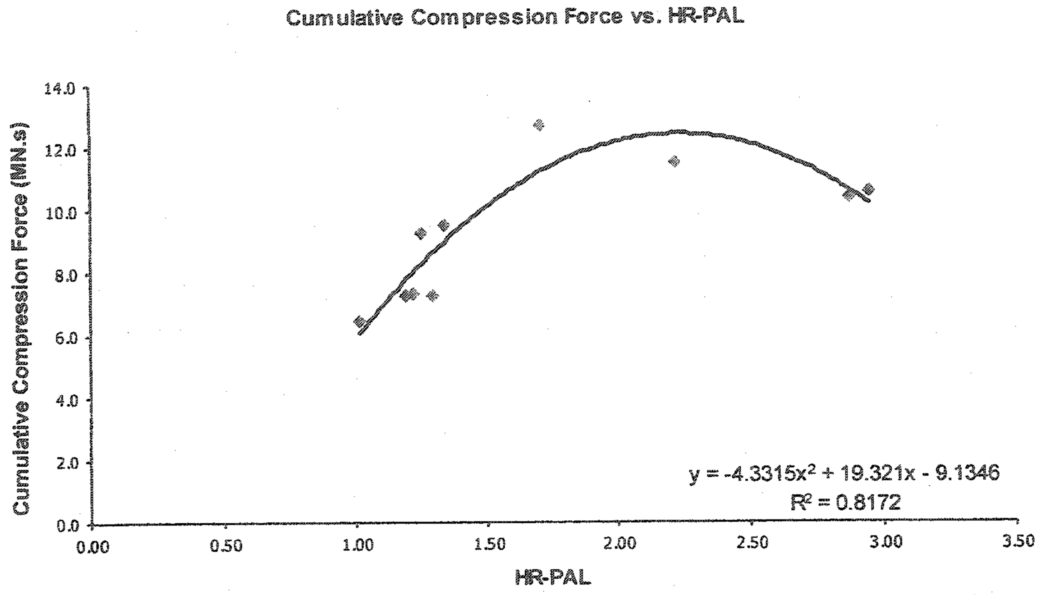

Figure 4a: Cumulative Compression Force vs. HR-PAL.

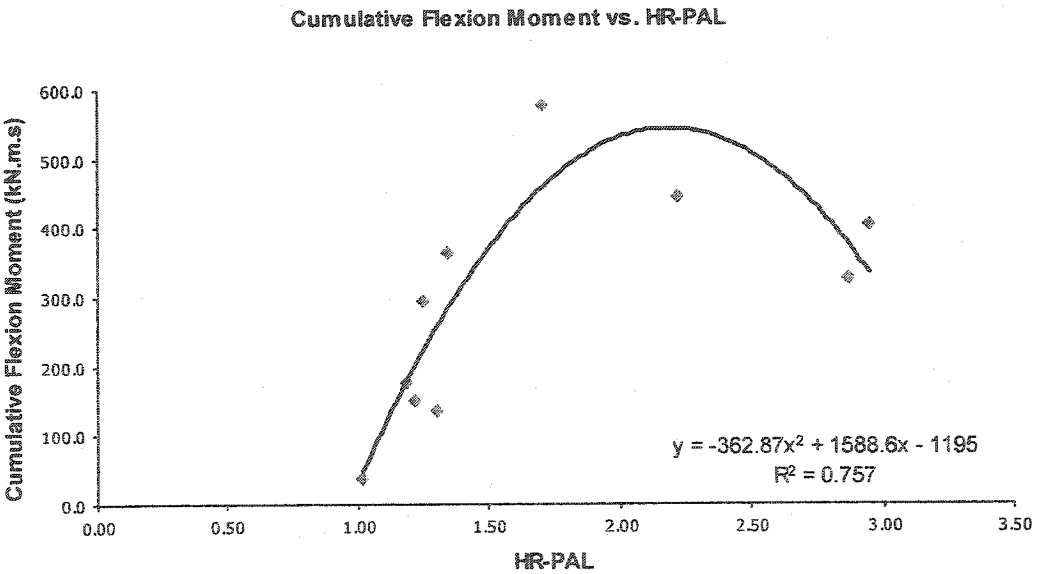

Figure 4b: Cumulative Flexion Moment vs. HR-PAL

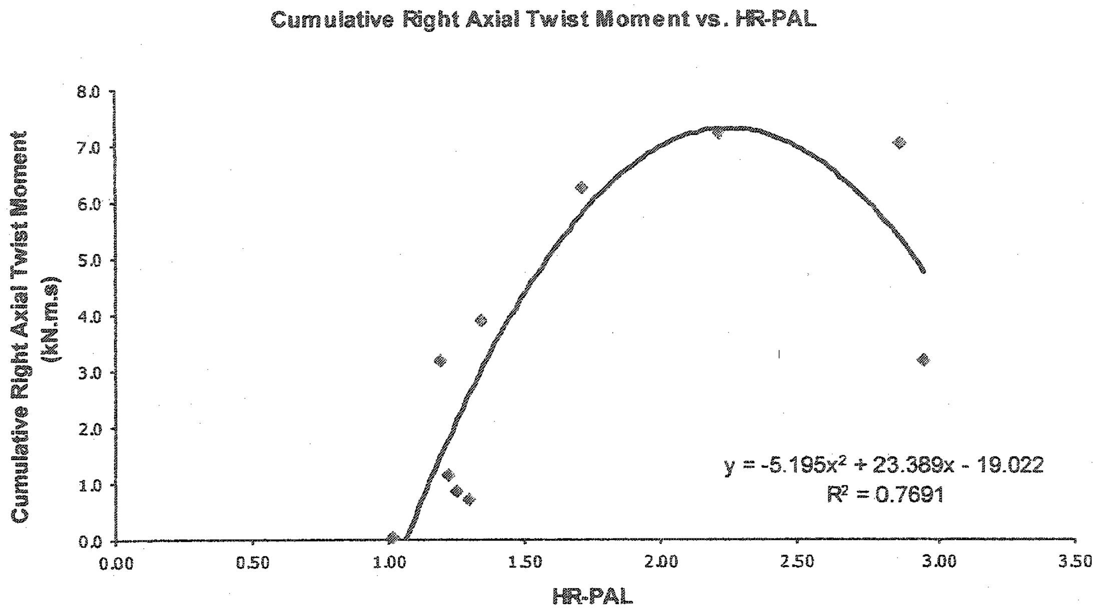

Figure 4c: Cumulative Right Axial Twist Moment vs. HR-PAL

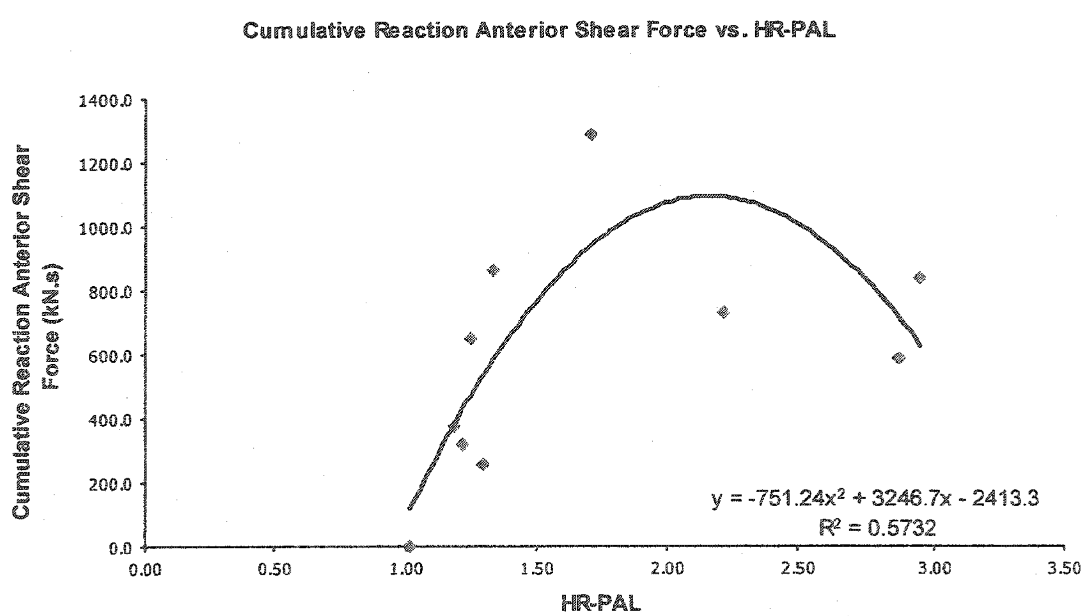

Figure 4d: Cumulative Reaction Anterior Shear Force vs. HR-PAL

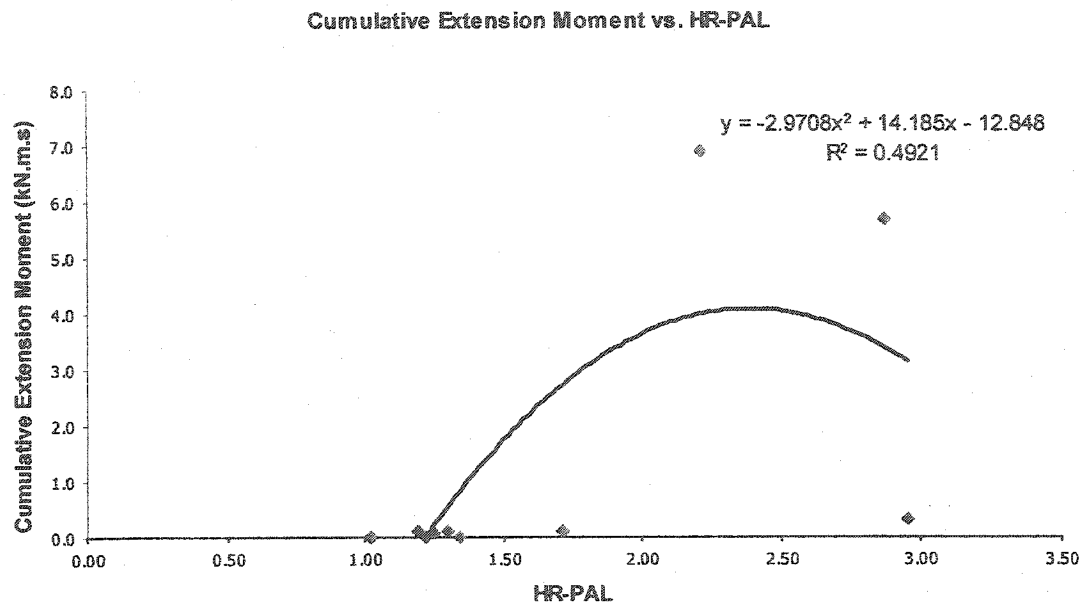

Figure 4e: Cumulative Extension Moment vs. HR-PAL

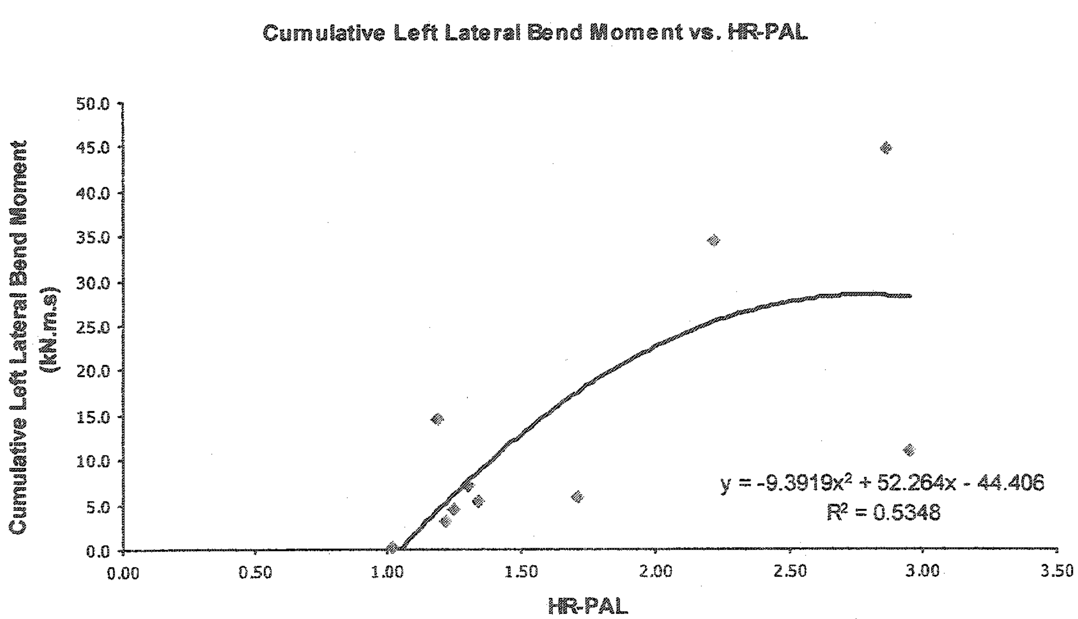

Figure 4f: Cumulative Left Lateral Bend Moment vs. HR-PAL

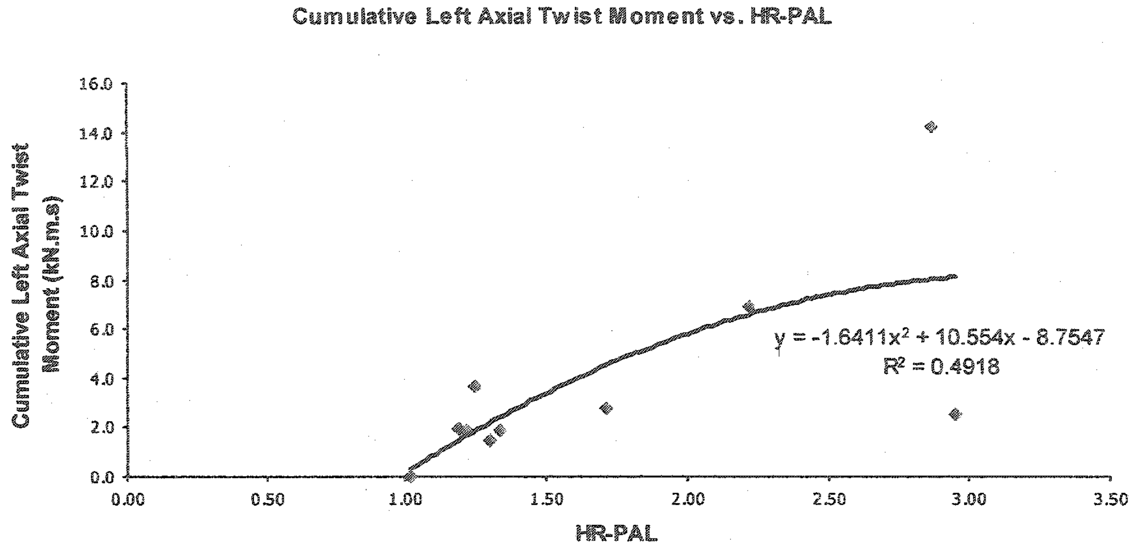

Figure 4g: Cumulative Left Axial Twist Moment vs. HR-PAL

4.3 Regression Validation

The validity of the predicted cumulative L4/L5 spinal loads and moments determined by HR-PAL was tested using the validation sample (*N* = 4). At an alpha level of 0.05, paired samples correlations revealed significant associations between the loads predicted from the regression equations (predicted; see Table 4 for equations) and the loads computed from video analysis (actual) for joint posterior shear force (Fig. 5a). When an alpha level of 0.01 was used, significant associations were found between predicted and actual loads for an additional three cumulative output variables: reaction posterior shear force (Fig. 5b), extension moment (Fig. 5c), and left axial twist moment (Fig 5d).

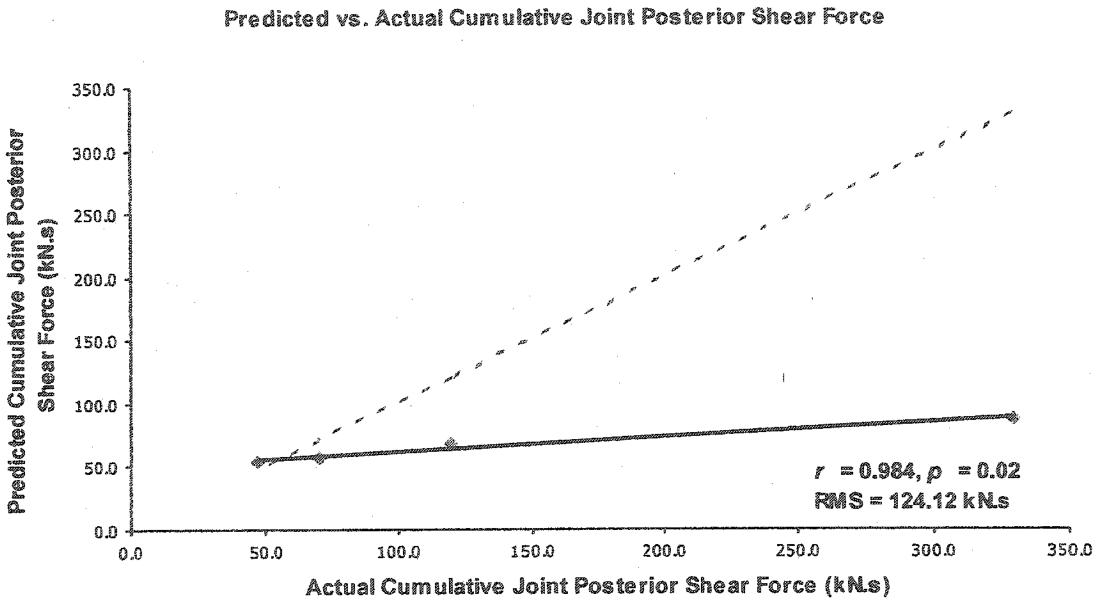

Figure 5a: Predicted vs. Actual Cumulative Joint Posterior Shear Force. Dotted line represents perfect prediction.

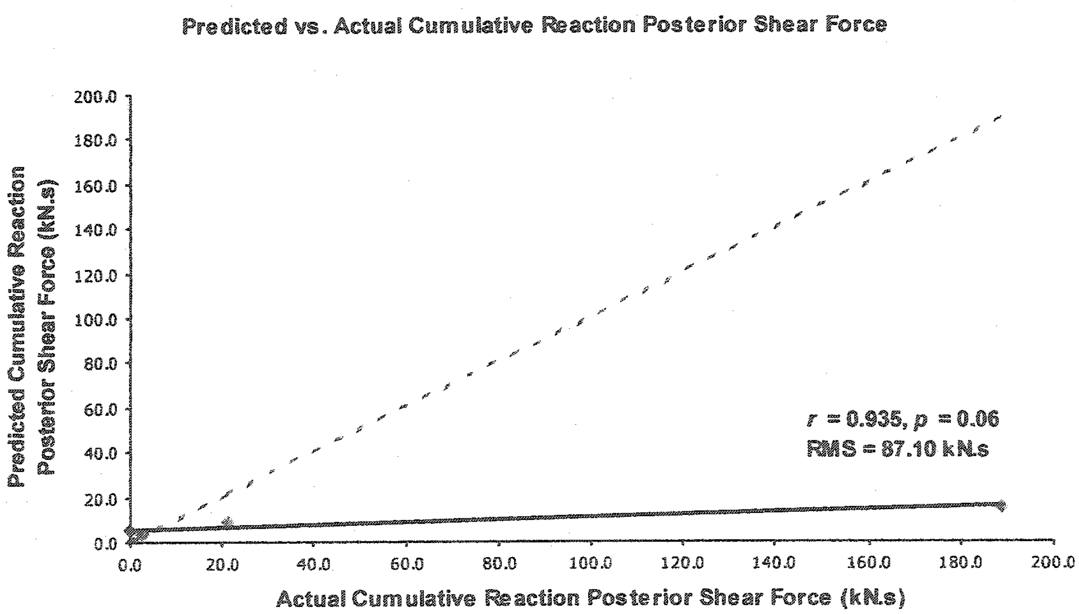

Figure 5b: Predicted vs. Actual Cumulative Reaction Posterior Shear Force. Dotted line represents perfect prediction.

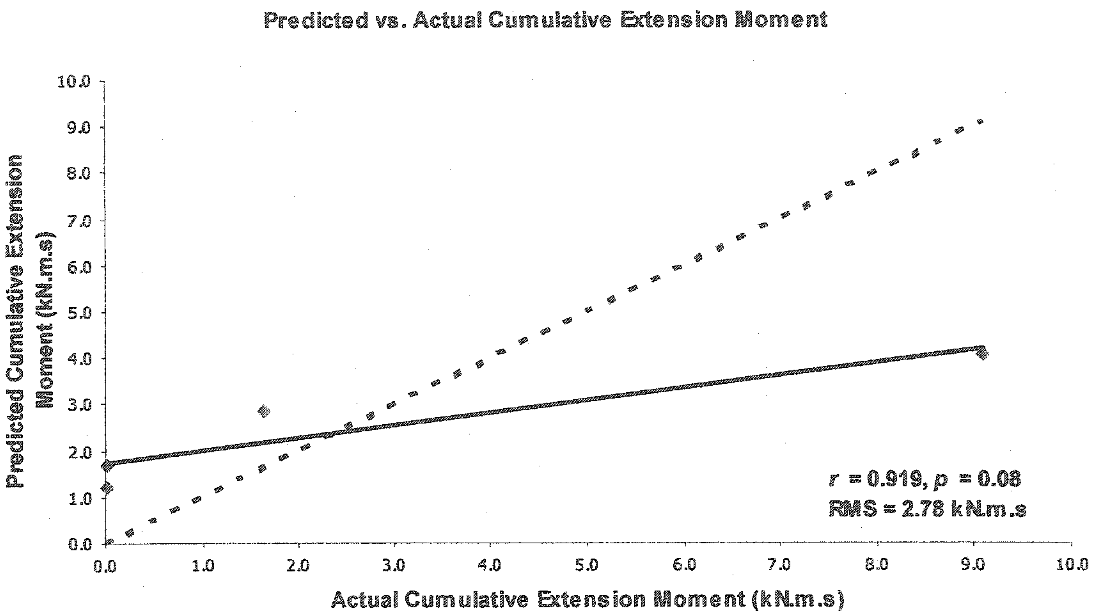

Figure 5c: Predicted vs. Actual Cumulative Extension Moment.
Dotted line represents perfect prediction.

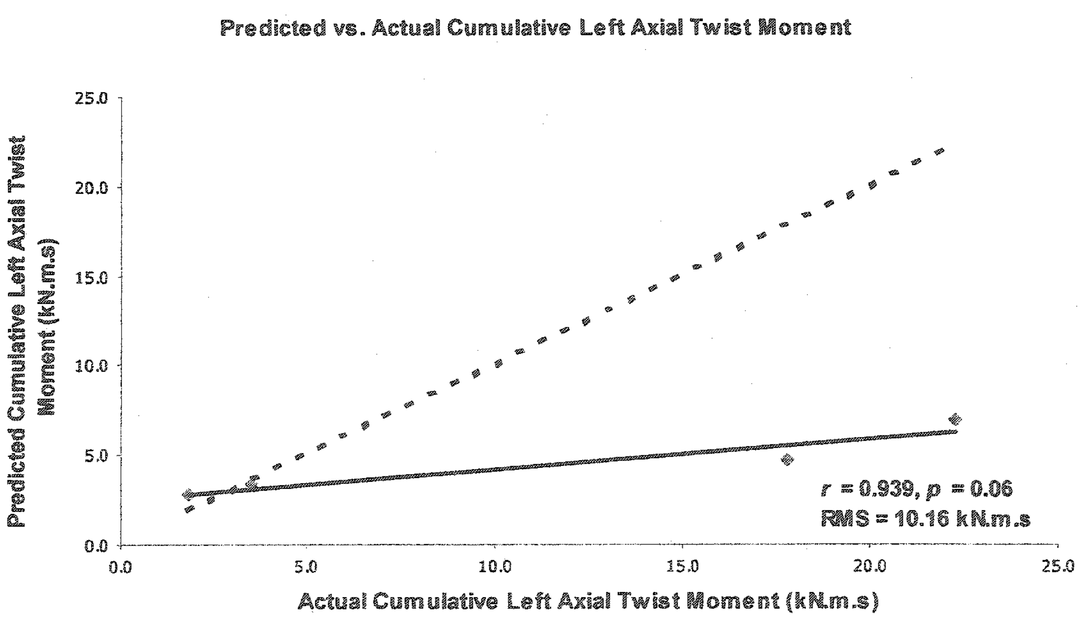

Figure 5d: Predicted vs. Actual Cumulative Left Axial Twist Moment.
Dotted line represents perfect prediction.

A summary of the *t*, *p*, and RMS errors for each load measure can be found in Table 5. At an alpha level of 0.05, paired samples *t*-tests revealed significant differences between predicted and actual compression force (t = -4.792, p = 0.02), reaction anterior shear force (t = -3.342, p = 0.04), and flexion moment (t = -3.797, p = 0.03). When an alpha level of 0.1 was used, significant differences were also found between predicted and actual joint anterior shear force (t = -2.437, p = 0.09). The root mean square (RMS) error between the predicted and actual loads was calculated in order to quantify the magnitude of the error in the predicted loads. RMS errors ranged from 2.78 kN·m·s for cumulative extension moment (on a maximum of 5.04 kN·m·s), to 2.44 MN·s for cumulative compression force (on a maximum of 3.50 MN·s).

Table 5: Comparison of Predicted and Actual Cumulative Loads. Boldface values are statistically significant at an alpha level of 0.05 (N = 4); italicized values are statistically significant at an alpha level of 0.1 (N = 4).

Cumulative Output Variable	*t*	*p*	RMS Error	Max Absolute Error
Compression Force (MN.s)	**-4.792**	**0.02**	2.44	3.50
Joint Anterior Shear Force (kN.s)	*-2.437*	*0.09*	170.49	215.88
Joint Posterior Shear Force (kN.s)	1.320	0.28	124.12	242.26
Reaction Anterior Shear Force (kN.s)	**-3.342**	**0.04**	547.40	737.16
Reaction Posterior Shear Force (kN.s)	1.046	0.37	87.10	173.68
Reaction Right ML Shear Force (kN.s)	-0.041	0.97	30.57	44.78
Reaction Left ML Shear Force (kN.s)	-0.687	0.54	32.59	40.57
Flexion Moment (kN.m.s)	**-3.797**	**0.03**	226.59	313.85
Extension Moment (kN.m.s)	0.154	0.89	2.78	5.04
Right Lateral Bend Moment (kN.m.s)	-1.036	0.38	13.46	18.78
Left Lateral Bend Moment (kN.m.s)	-0.198	0.86	9.38	13.02
Left Axial Twist Moment (kN.m.s)	1.636	0.20	10.16	15.44
Right Axial Twist Moment (kN.m.s)	0.619	0.58	10.47	20.56

Chapter V
Discussion

The regression equations relating heart rate determined physical activity level (HR-PAL) to cumulative L4/L5 spinal loads and moments generated in the present study, were able to account for a significant amount of variance in three of the 13 cumulative output variables (compression force, flexion moment, and right axial twist moment), when an alpha level of 0.05 was used. Approximately 76-82% of the variance in these cumulative loading variables was accounted for. When an alpha level of 0.10 was used, the regression equations were able to account for a significant amount of variance in an additional four variables (reaction anterior shear force, extension moment, left lateral bend moment, and left axial twist moment). The proportion of variance accounted for in these variables ranged from approximately 49-57%. At an alpha level of 0.05, a significant correlation was found between predicted and actual cumulative loads for cumulative joint posterior shear force, and significant differences were found between predicted and actual cumulative compression force, reaction anterior shear force, and flexion moment. When the alpha level was set at 0.1, three additional variables showed significant correlations between predicted and actual loads (reaction posterior shear force, extension moment, and left axial twist moment), and only one additional variable showed a significant difference between predicted and actual loads (joint anterior shear force).

5.1 Hypotheses Revisited

5.1.1 Research Hypothesis #1

HR-PAL will account for a significant amount of variance in all seven cumulative L4/L5 spinal loads (compression, anterior and posterior joint shear forces, anterior and posterior reaction shear forces, and right and left mediolateral reaction shear forces) and six cumulative L4/L5 moments (extension and flexion moments, right and left lateral bend moments, and right and left axial twist moments).

In the present study, HR-PAL was able to account for 75.7-81.7% of the variance in cumulative compression force, flexion moment, and right axial twist moment. The variance accounted for in these three variables was statistically significant at an alpha level of 0.05. However, the functional significance of the results must also be considered. When the alpha level is changed to 0.1, HR-PAL can account for a significant amount of variance in four additional variables (reaction anterior shear force, extension moment, left lateral bend moment, and left axial twist moment). Thus, HR-PAL was able to account for a significant proportion of variance in a total of seven out of 13 cumulative output variables. It is encouraging that the cumulative output variable with the largest proportion of variance accounted for, was compression force. This finding is particularly significant, because L4/L5 compression force is commonly used to determine risk of injury to the low back.

5.1.2 Research Hypothesis #2

There will be no significant differences between actual loads (estimated by video) and predicted loads (from HR-PAL equations) for any of the cumulative L4/L5 spinal loads (compression, anterior and posterior joint shear forces, anterior and posterior reaction shear forces, and right and left mediolateral reaction shear forces) and cumulative L4/L5 moments (extension and flexion moments, right and left lateral bend moments, and right and left axial twist moments).

When the validation sample was used to compare predicted and actual cumulative output variables, three of the seven variables with significant R^2 values ($p = 0.1$) showed significant differences between predicted and actual loads (compression force, reaction anterior shear force, and flexion moment). However, of the six output variables that did not return significant R^2 values, only joint anterior shear force showed significant differences between predicted and actual loads (Table 5). This was likely a result of the size of the validation sample. A larger sample may have increased the possibility of finding significant differences between predicted and actual loads in variables with non-significant R^2 values; also, it may have decreased the possibility of finding significant differences between predicted and actual loads in variables with significant R^2 values.

5.2 Additional Predictor Variables

Approximately 53-92% of the variance in the remaining six cumulative output variables remains unaccounted for. Therefore, HR-PAL is likely not the only predictor of cumulative L4/L5 spine loads and moments. Other variables that were considered for use as model development inputs include subject mass, height, age, and gender. These are also inputs used to generate HR-PAL values, thus they could not be used alongside HR-PAL as separate model development variables, since they would be highly correlated. Another variable that could have been used is body composition. The weight of the upper body contributes to the magnitude of the loads generated at L4/L5. Muscle weighs more than fat, thus a higher % body fat may be inversely related to the loads on

L4/L5. Body composition was not used as a predictor variable in the present study because of the error involved, both in measuring body composition directly and predicting body composition from equations.

5.3 Curve Estimation

The relationship between HR-PAL and estimates of cumulative L4/L5 spine loads and moments was examined using linear regression and several higher order polynomials. Second order polynomial provided the best fit in general, based on the amount of variance in the dependent measures accounted for by HR-PAL. The linear equations were able to account for 0.2 – 49.7% of the variance in cumulative load estimates. When the relationship was considered to be quadratic, the variance accounted for increased by 7.6 – 32%. The amount of variance accounted for with the quadratic functions ranged from 7.8% of the variance in cumulative reaction left mediolateral shear force, to 81.7% of the variance in cumulative compression force. Higher order polynomials (e.g. cubic) were able to account for even more variance, but the quadratic equations were chosen for further analysis because similar looking non-linear relationships have been shown to exists between many biological parameters (biomechanical and physiological) in the literature. Take for example, the effect of increased temperature on enzyme activity. Over a particular range of temperatures, enzyme activity increases as body temperature increases. Each enzyme has a particular temperature range at which it functions optimally. If the temperature continues to increase over the optimal temperature range of the enzyme, denaturation occurs and enzyme activity decreases (Robergs and Roberts, 1997). Other examples of physiological and biomechanical relationships that assume this shape graphically include the muscle length-tension relationship (Whiting and Zernicke, 1998), the effect of arousal on performance (Schmidt, 1991), and the effect of aging on mean total response speed (Spirduso, 1995).

In addition to the similarity in shape compared to other biological relationships, an inverted quadratic relationship between cumulative load (e.g. flexion moment, Figure 4b) and HR-PAL makes biomechanical and physiological sense. The shape of the relationship between HR-PAL and several of the demographic variables used in the present study supports this notion. For instance, when subject mass is plotted against HR-PAL, the shape of the curve is similar to the curve in Figure 4b. The lightest and heaviest subjects had the lowest and highest HR-PAL values, respectively, while subjects with mid-range masses had mid-range HR-PAL values, creating an inverted U-shaped curve. Subject height and average hand load follow the same trend. Since hand load, subject mass, and subject height all contribute to the magnitude of flexion moment, it follows that all four of these variables should have similar shapes when plotted against HR-PAL. It should be noted that the HR-PALs ranged from light to moderate in this study, and so it is unknown if the quadratic relationship between HR-PAL and cumulative loads at higher activity levels will hold.

5.4 Cumulative Loading in Non-occupational Settings

Consideration of cumulative loads in conjunction with peak loads is likely to improve our ability to predict those at risk of reporting LBP. Examining the cumulative and peak loads occurring in non-occupational settings is likely to improve our predictive ability even further. The mean cumulative compression reported in the present study (8.31 ± 2.9 MN·s) compares favourably with the 10.08 ± 6.1 MN·s reported by Lauder and Andrews (2002), and the 6.56 ± 1.2 MN·s reported by Azar et al. (2003). However, the data of both Lauder and Andrews (2002) and Azar et al. (2003) was generated using 2-dimensional biomechanical models. The model used in the present study was 3-dimensional, thus an appropriate comparison between the three studies cannot be drawn.

Godin et al. (2003) documented both the peak and cumulative loads sustained during non-occupational tasks, using the 3-D Match biomechanical analysis software (University of Waterloo, Waterloo, Ontario). Subjects performed self-paced, self-determined non-occupational tasks for a period of 2 hours, similar to the present study. A comparison of the results of Godin et al.

Table 6: Comparison of Results. Cumulative L4/L5 spinal loads and moments reported in the present study and in Godin et al. (2003). Both studies used the same data collection and processing methods, and the same biomechanical analysis, but different subject pools. The similarity in their results is evident.

Cumulative Output Variable	Present Study	Godin et al. (2003)
Compression Force (MN.s)	9.2 (2.1)	7.8 (3.1)
Joint Anterior Shear Force (kN.s)	163.2 (123.3)	105.1 (81.1)
Joint Posterior Shear Force (kN.s)	79.5 (81.1)	95.2 (92.3)
Reaction Anterior Shear Force (kN.s)	486.3 (359.1)	311.0 (290.4)
Reaction Posterior Shear Force (kN.s)	19.4 (50.1)	24.7 (59.1)
Reaction Right Mediolateral Shear Force (kN.s)	19.4 (25.4)	3.7 (5.6)
Reaction Left Mediolateral Shear Force (Kn.s)	24.6 (32.2)	11.6 (15.7)
Extension Moment (kN.m.s)	249.4 (163.7)	201.0 (142.8)
Flexion Moment (kN.m.s)	1.7 (3.1)	1.2 (2.8)
Right Lateral Bend Moment (kN.m.s)	13.5 (11.9)	10.4 (6.5)
Left Lateral Bend Moment (kN.m.s)	12.3 (13.0)	7.1 (5.3)
Left Axial Twist Moment (kN.m.s)	5.6 (7.1)	4.5 (7.1)
Right Axial Twist Moment (kN.m.s)	4.8 (6.8)	2.0 (2.5)

(2003) and the results of the present study can be found in Table 6. Both studies employed similar data collection and processing methods and the same biomechanical analysis software, but with completely different subject pools. To date, these are the only studies that have been conducted using 3-dimensional biomechanical analysis to document cumulative low back loads in non-occupational settings. Further investigation in occupational settings for the basis of comparison to the non-occupational data collected here and by Godin et al. (2003), is warranted.

5.5 Physical Activity Level

The median HR-PAL for the generation and validation samples in the present study, as well as those for Rennie et al. (2001) are presented in Table 7. The HR-PAL values from the two studies are comparable, with one notable difference. Subjects in the Rennie et al. (2001) study wore heart rate monitors during waking hours for four consecutive days. These days included both weekdays and weekends, thus it is likely that the PALs reported by Rennie et al. (2001) were generated during both occupational and non-occupational tasks.

Table 7: PAL Comparison. Median (interquartile range) PAL values found in the present study and by Rennie et al. (2001). Rennie et al. (2001) included the collection of occupational tasks in addition to non-occupational tasks, which may explain the differences between studies.

			Median (interquartile range)
Present Study	Generation Sample	Males	2.22 (1.70, 2.87)
		Females	1.25 (1.22, 1.30)
	Validation Sample	Males	2.03 (1.88, 2.17)
		Females	1.45 (1.42, 1.47)
Rennie et al. (2001)	Generation Sample	Males	1.93 (1.67, 2.21)
		Females	1.72 (1.51, 1.93)
	Validation Sample	Males	1.60 (1.48, 2.06)
		Females	1.95 (1.52, 2.40)

Some of the differences between the PALs reported in the two studies may be attributed to the type of occupational tasks the subjects performed (i.e. whether their jobs were physically demanding or not).

5.6 Limitations

5.6.1 Number of Subjects

Originally, twenty subjects was the desired number of subjects to be recruited for this study. Due to recruitment and data collection problems, usable data was only collected on 14 subjects. Ten subjects were used to generate the regression models, and four subjects were used to test the models. The models generated in the present study were derived using simple linear regression, with a single independent variable. Ten subjects is the minimum recommended number of subjects per independent variable (Oser et al., 1997), thus the number of subjects used in the present study is not considered to be a major limitation.

5.6.2 Population Specific Results

The age range of the subjects in this study was chosen to match the age range specified by Rennie et al. (2001) to predict HR-PAL. The age range of the subjects used in this study is believed to accurately represent the typical age range of the working population. The subjects in the present study were taken from the general population, and the results of this study may be more readily applied to the rest of the general public than if we had used a sample comprised of university students. The subjects in this study also more accurately represent the non-occupational demands of the general working public. A sample comprised of university students would not accurately represent these demands, as most students are not parents, do not own homes, or do not hold full-time jobs.

5.6.3 Heart Rate Collection and Potential Confounds

Heart rate is influenced by several external factors, including emotion, posture, use of stimulants (caffeine, nicotine) or depressants (alcohol), altitude, and climate (Haskell et al., 1993, Hiilloskorpi et al., 1999, Rennie et al., 2001). Higher measurements of heart rate would result in an inflated HR-PAL value, which in the present study would have resulted in larger predicted cumulative L4/L5 spinal loads and moments. In an effort to counteract this, subjects were asked to refrain from smoking, alcohol, and caffeine intake prior to data collection. However, it is possible that the subjects did not adhere to these requirements. To reduce the influence of these factors, sitting heart rate was collected immediately prior to initiating data collection. To counteract the effect of subject nervousness on heart rate measurement, the first ten minutes of data collection were used as an acclimatization period. Although the heart rate monitor was initiated, the subject was unaware that the camera was not recording. This allowed them to alleviate any nervousness, so that once video data collection was initiated, they had settled into their routine and had become accustomed to the presence of the investigators and the video camera in their home. Finally, some subjects noted that they were performing their tasks more slowly than they normally would, to allow the investigators to follow them and maintain their camera angle as much as possible. This may have resulted in lower heart rate readings, which in the present study, would have resulted in lower HR-PAL values, leading to an underestimation of the predicted cumulative L4/L5 spinal loads and moments.

5.6.4 Static Modeling of Dynamic Activities

The conclusions reached in this study may be limited due to the use of a static model to represent dynamic activities. Documenting dynamic cumulative loading exposure using video-based methodologies, such as the one employed in the present study, would require a great deal of extra collection and analysis time and expertise that are generally not possible or are impractical in industrial or home settings. The use of a static model to represent dynamic tasks has been employed in several other studies in the literature in this area (Kumar, 1990; Norman et al., 1998; Daynard et al., 2001).

5.6.5 Biomechanical Model

The 3-D Match analysis tool allows you to indicate the magnitude of the load held in the hands, as well as the direction in which that load is acting (e.g. lift/lower; push/pull forward, back, left, or right). However, the model does not take into account loads that are acting at a distance from the hands, such as when lifting a load with a shovel. Loads acting outside the hands have a greater effective mass, due to the large moment arm of the load. This results in an underestimation of the cumulative output variables. Fortunately, tasks such as shoveling were not encountered in the present study. Although many subjects used brooms, the load caused by the broom could be assumed to act at the hands, since the broom was not used to lift an additional load.

5.7 Conclusions

Cumulative loading has been established as a contributing factor in the risk of reporting low back pain. Current methods of collecting cumulative loading can be time-consuming and expensive, especially when investigating non-repetitive, non-occupational tasks. The present study sought to quantify the relationship between physical activity level, as estimated by Rennie et al. (2001) using minute-by-minute heart rate monitoring, and estimates of cumulative low back loads estimated from video records of non-occupational activities. The establishment of a sufficiently strong relationship between heart rate determined physical activity level (HR-PAL) and cumulative low back loads, would possibly reduce the need for video documentation in future biomechanical analyses, making it possible for cumulative load assessment to be conducted over longer periods of time, at a much reduced cost. The results of the present study indicate that HR-PAL can account for a significant proportion of variance in some, but not all, of the cumulative output variables investigated here. Furthermore, HR-PAL was able to account for approximately 76-82% of the variance in those cumulative output variables whose proportion of variance accounted for by HR-PAL was significant, most notably for cumulative compression. The present study was an exploratory study into the link between physiological variables and biomechanical outcomes, the first study of its kind. While HR-PAL shows promise in its ability to predict cumulative L4/L5 spine loading, further investigation of this relationship is needed.

5.8 Recommendations for Future Research

1) HR-PAL is likely not the only predictor of cumulative L4/L5 spine loads and moments. Future studies should investigate the presence of additional variables (such as body composition) that could improve the prediction power of these regression equations.
2) Further 3-dimensional analysis of cumulative L4/L5 spinal loads and moments during non-occupational activities are needed. To date, only two studies have been conducted to document such loading. More research is necessary to broaden the available data in this area.
3) Combined with the knowledge of the loading that occurs in non-occupational settings, quantification of 3-dimensional cumulative L4/L5 spinal loads and moments incurred in occupational settings would further improve the ability to predict who is at risk for low back pain. Future studies should attempt to document the 3-dimensional cumulative loading during occupational activities.
4) This study considered the relationship between cumulative low back loads and HR-PAL across a range of activities with low to moderate associated energy requirements. Future studies should investigate this relationship across a range of activities with moderate to high associated energy requirements.

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APPENDIX A

Ethics Approval

APPENDIX B

Information and Informed Consent

UNIVERSITY OF WINDSOR

CONSENT TO PARTICIPATE IN RESEARCH

An Examination of non-occupational tasks and their effects on low back pain

Using levels of energy expenditure to predict cumulative lumbar spine loading

You have been asked to participate in a research study conducted by Dr. Dave Andrews, Christina Godin (M.H.K candidate), and Nadia Azar (M.H.K candidate) from the Faculty of Human Kinetics at the University of Windsor, Dr. Pam Bryden from the Department of Kinesiology and Physical Education at Wilfrid Laurier University, and Dr. Wayne Albert from the Department of Kinesiology at the University of New Brunswick. This project is funded by Auto 21 NCE (Networks of Centers of Excellence). If you have any questions or concerns about the research, please feel free to contact:

Dr. Dave Andrews	Christina Godin	Nadia Azar
Faculty of Human Kinetics	Faculty of Human Kinetics	Faculty of Human
Kinetics		
University of Windsor	University of Windsor	University of Windsor
(519) 253-3000, ext. 2433	godin4@uwindsor.ca	n.azar@cogeco.ca

PURPOSE OF THE STUDY

The objectives of this study are:

a) To determine the cumulative loads associated with non-occupational activities through video documentation.
b) To determine the relationship between energy expenditure levels and cumulative lumbar spine loads.

BACKGROUND

Traditionally, exposure to risks for injury in the workplace has been the focus of biomechanical analyses of the low back. However, little attention has been given to the potential contribution of non-occupational activities. Cumulative loading of the lumbar spine has recently been identified as a significant risk factor for reporting low back pain. However, collection of cumulative load data is time consuming and expensive. Recent research has succeeded in reducing the time requirements of data collection, but the costs of data collection remain considerable. If a relationship can be established between heart rate and cumulative low back load (associated with the amount of physical activity of the subjects), significant time and expense related to the collection and analysis of hours of video recordings could be spared. The purpose of this study is to document the activities performed within the home and thus determine the cumulative loads of non-occupational tasks.

PROCEDURES

If you choose to participate in this study the following timeline will apply:
The study will be conducted over one session. Background information on the study will be provided and you will be asked to review and sign the informed consent form.

Information such as height, mass, age, and gender will be recorded in a brief interview. At this time, you will be asked to wear a heart rate monitor (consisting of a chest strap and wristwatch). The monitor will remain in place and record your heart rate for the duration of the session. The chest strap component of the heart rate monitor must be placed over the sternum and attached around the back with an elastic strap, underneath your normal clothing. After this point you will be instructed to resume your regular daily routine. An acclimatization period will pass before the camera and the heart rate monitor are turned on. This will allow you to adapt to the presence of a researcher in your home. You will be reminded that there are no limitations or constraints for the tasks you wish to perform. A total of two hours of task performance will be recorded continuously on videotape. At the end of the session, the researcher will use a scale to determine the weight of each object lifted, or the push and pull forces that you exert on objects during the two hours of task performance. After analysis of the videotape, the researchers may determine that a second session is necessary. The purpose of the second session will be to recreate certain tasks performed in the first session that were not clearly visible on video. You will not be required to wear the heart rate monitor. Each task will be re-recorded for approximately one minute. Depending on the number of tasks, this session may last between 30-60 minutes.

POTENTIAL RISKS AND DISCOMFORTS

Since this study involves performing non-occupational tasks, the risks are minimal. However, it is possible that as a result of being videotaped, you may choose to perform active tasks continuously rather then engaging in quiet activities or rest. As a result, you may experience some fatigue, particularly within the back muscles. The heart rate monitors to be used are standard exercise units that anyone can purchase readily at any sports store and do not pose any physical risk. Subjects may feel somewhat self-conscious wearing the monitor at first, but tend to forget it is there very readily. The chest strap will be applied with only one investigator present, in a private location (i.e. bathroom). Also, participants will be allowed to decline to wear the monitor and still participate in the video portion of the data collection if the heart rate monitors cause any sort of discomfort. In addition, feelings of anxiety or self- consciousness may be elicited as a result of having your actions recorded. To minimize the potential for risk, the researcher will allow for an adjustment period, where you will have the opportunity to become familiar with the presence of a camera before recording begins. *Participation in this study is strictly voluntary, and thus you are free to withdraw at any time.*

POTENTIAL BENEFITS TO SUBJECTS AND/OR SOCIETY

Participation in this study will provide the opportunity to learn about the research currently being conducted within your academic institution and to learn about the process of data collection in field studies. In addition, you may benefit from knowing that the data collected will enable researchers to better predict the risk of injury associated with performing non-occupational activities. If a relationship can be established between heart rate and cumulative low back load (associated with the amount of physical activity of the subjects), researchers in this field could potentially be spared significant time and expense related to the collection and analysis of hours of video recordings. In addition, if the heart rate monitors prove to be a valid tool, then video analysis would not be needed.

As such, subjects would be able to go about their normal daily activities in private at home without being interfered with at all by the investigator during data collection.

PAYMENT FOR PARTICIPATION

You will not receive remuneration for participation in this study.

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.

Only the investigators will have access to the data. All data will be stored in a locked lab within the Department of Human Kinetics at the University of Windsor and will remain there for a period of two years, at which point it will be destroyed. A participant number in place of your name will be used to code the data and as such you will never be identified. In addition, the results of the study will not include your individual data unless you have given prior consent. You have the right to review and edit your recordings following completion of data collection.

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 decline to wear the heart rate monitor and still participate in the video portion of the data collection. You may exercise the option of removing your data from the study. 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.

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 Co-ordinator
Telephone: 519-253-3000, # 3916
E-mail: ethics@uwindsor.ca
University of Windsor
Windsor, Ontario
N9B 3P4

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study "An Examination of non occupational tasks and their effects on low back pain" 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	Date
Signature of Subject	Date

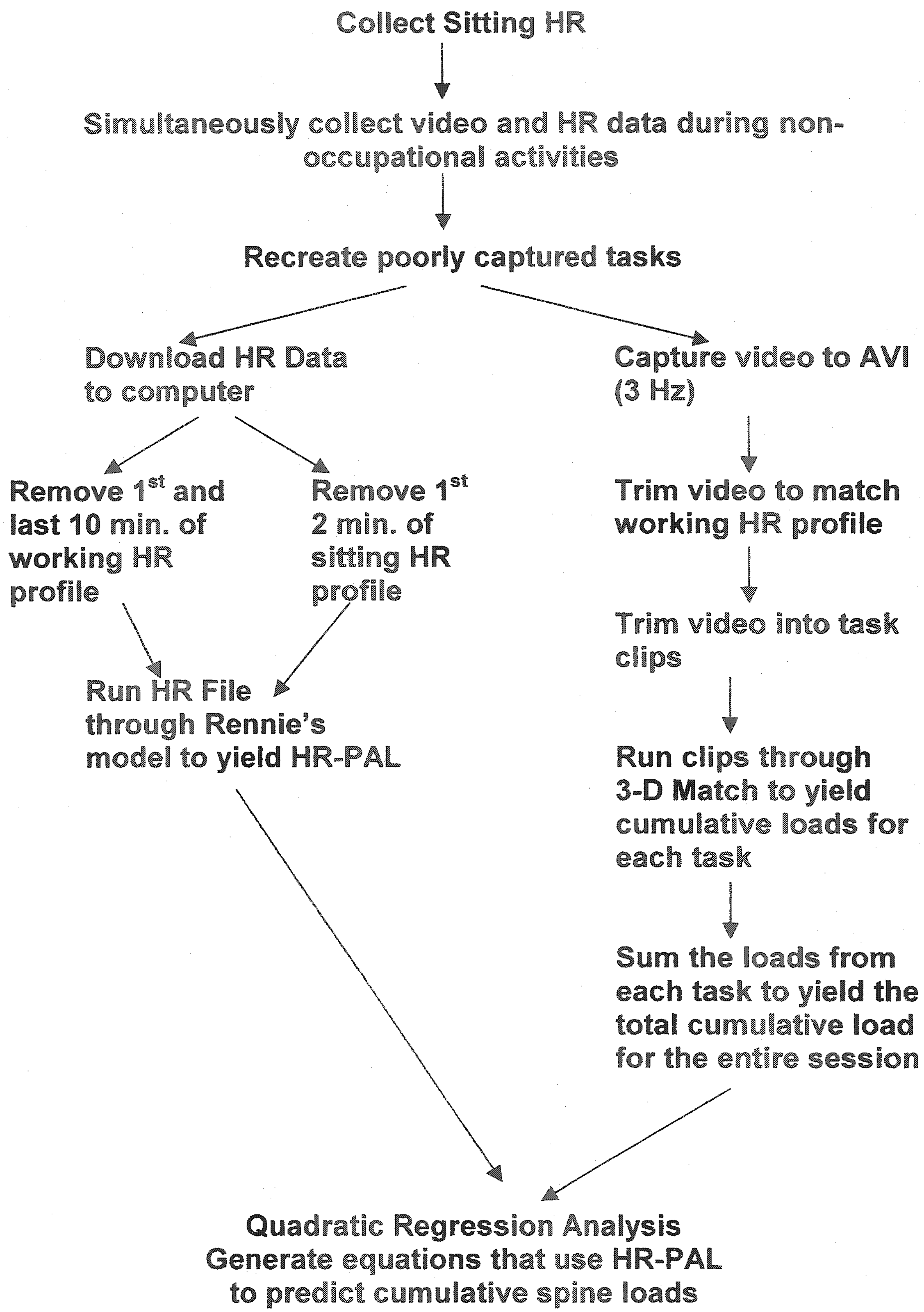
SIGNATURE OF INVESTIGATOR

In my judgment, the subject is voluntarily and knowingly giving informed consent to participate in this research study.

Signature of Investigator	Date
Signature of Investigator	Date

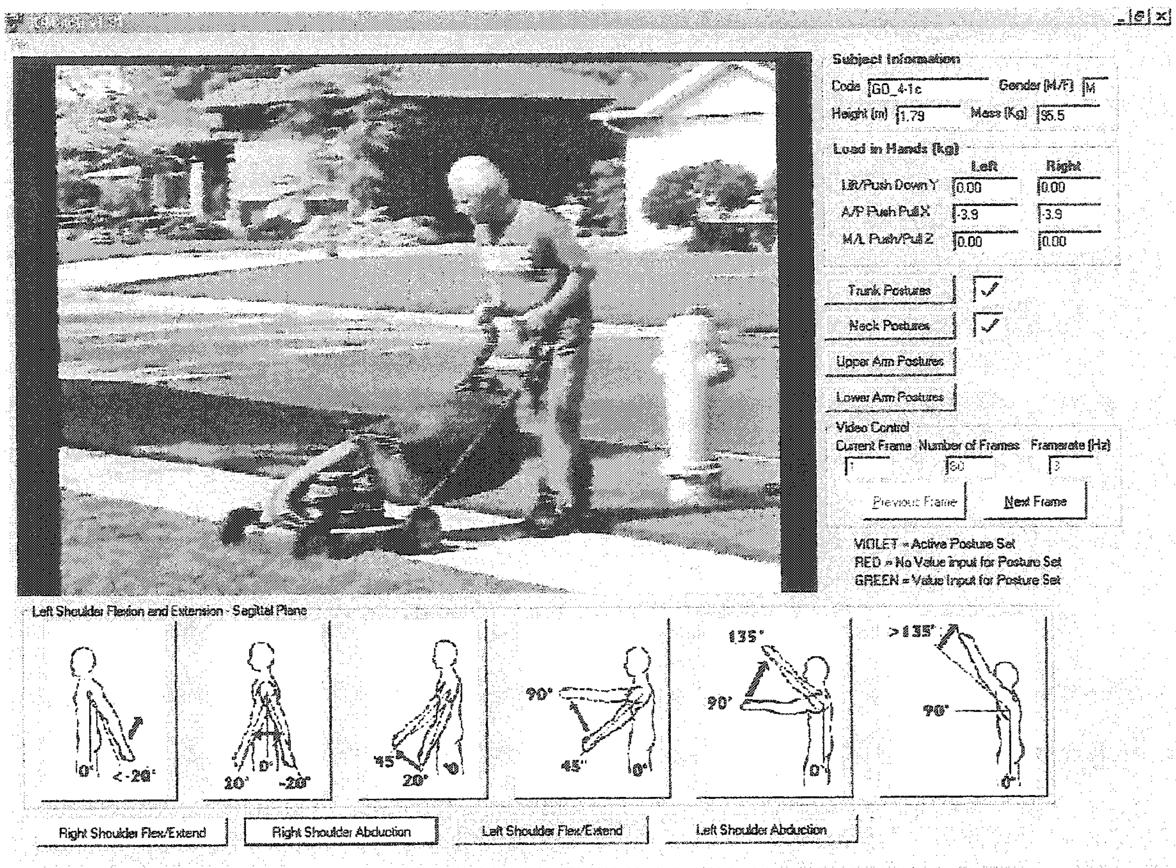
APPENDIX C

Data Collection and Analysis Flow-Chart


Collect Sitting HR
Simultaneously collect video and HR data during non-occupational activities
Recreate poorly captured tasks
Download HR Data to computer
Capture video to AVI (3 Hz)
Remove 1st and last 10 min. of working HR profile
Remove 1st 2 min. of sitting HR profile
Trim video to match working HR profile
Trim video into task clips
Run HR File through Rennie's model to yield HR-PAL
Run clips through 3-D Match to yield cumulative loads for each task
Sum the loads from each task to yield the total cumulative load for the entire session
Quadratic Regression Analysis
Generate equations that use HR-PAL to predict cumulative spine loads

APPENDIX D

3-D Match User Interface

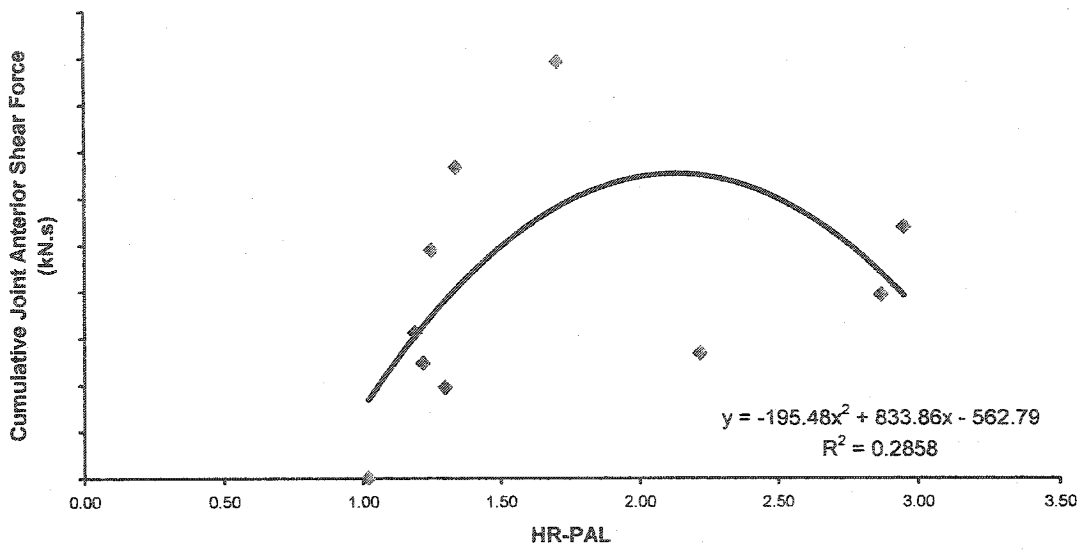


Subject Information
Code GD_4-1c
Gender (M/F) M
Height (m) 1.79
Mass (Kg) 95.5
Load in Hands (kg)
Left
Right
Lift/Push Down Y 0.00 0.00
A/P Push Pull X -3.9 -3.9
M/L Push/Pull Z 0.00 0.00
Trunk Postures
Neck Postures
Upper Arm Postures
Lower Arm Postures
Video Control
Current Frame
Number of Frames
Framerate (Hz)
Previous Frame
Next Frame
VIOLET = Active Posture Set
RED = No Value input for Posture Set
GREEN = Value Input for Posture Set
Left Shoulder Flexion and Extension - Sagittal Plane
0°
<-20°
20°
0°
-20°
45°
20°
0°
90°
45°
0°
135°
90°
0°
>135°
90°
0°
Right Shoulder Flex/Extend
Right Shoulder Abduction
Left Shoulder Flex/Extend
Left Shoulder Abduction

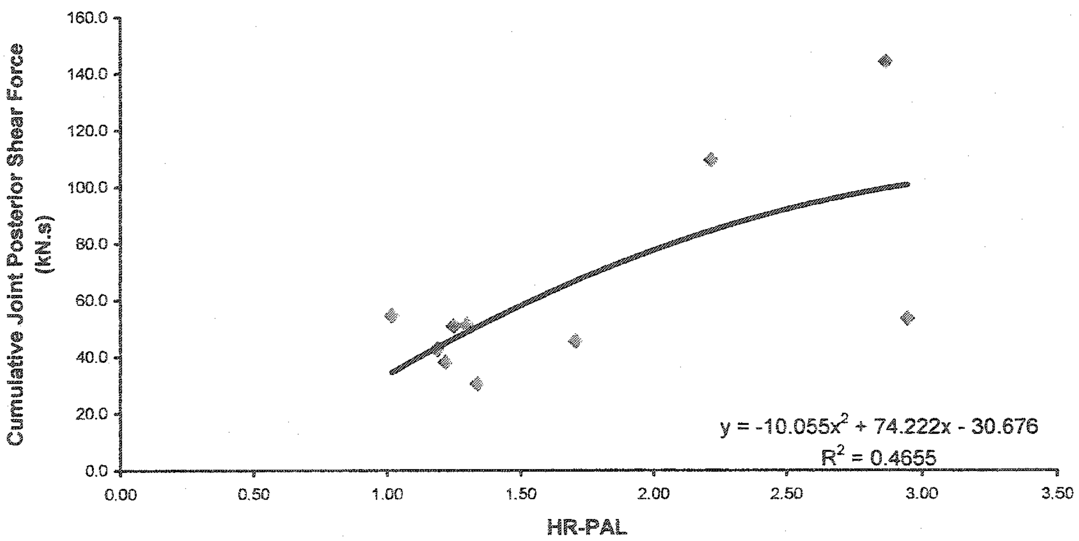
APPENDIX E

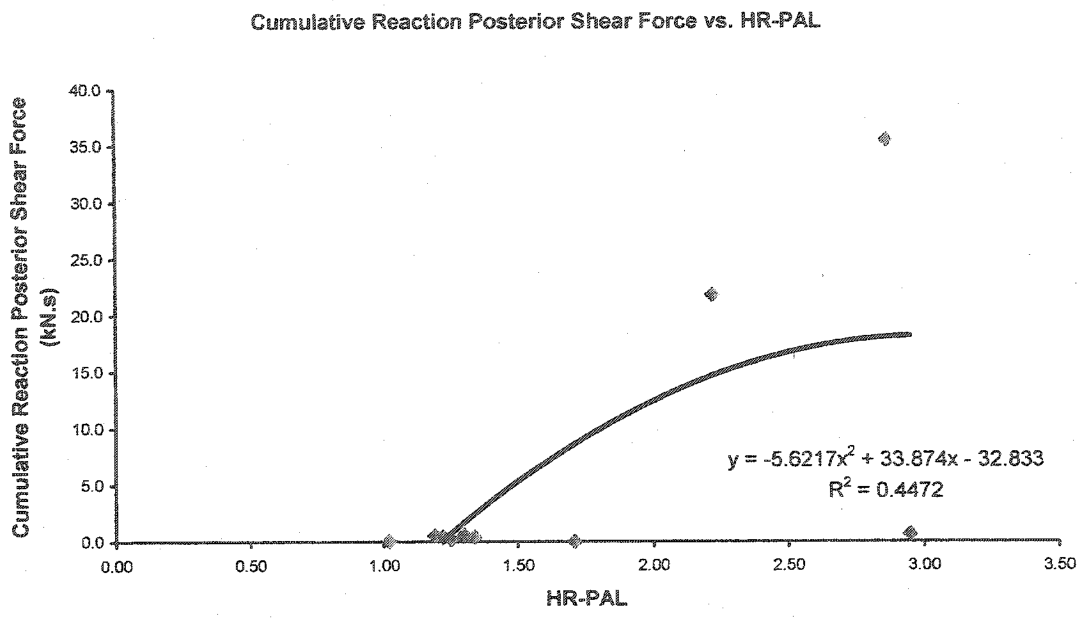
Non-Significant Regressions

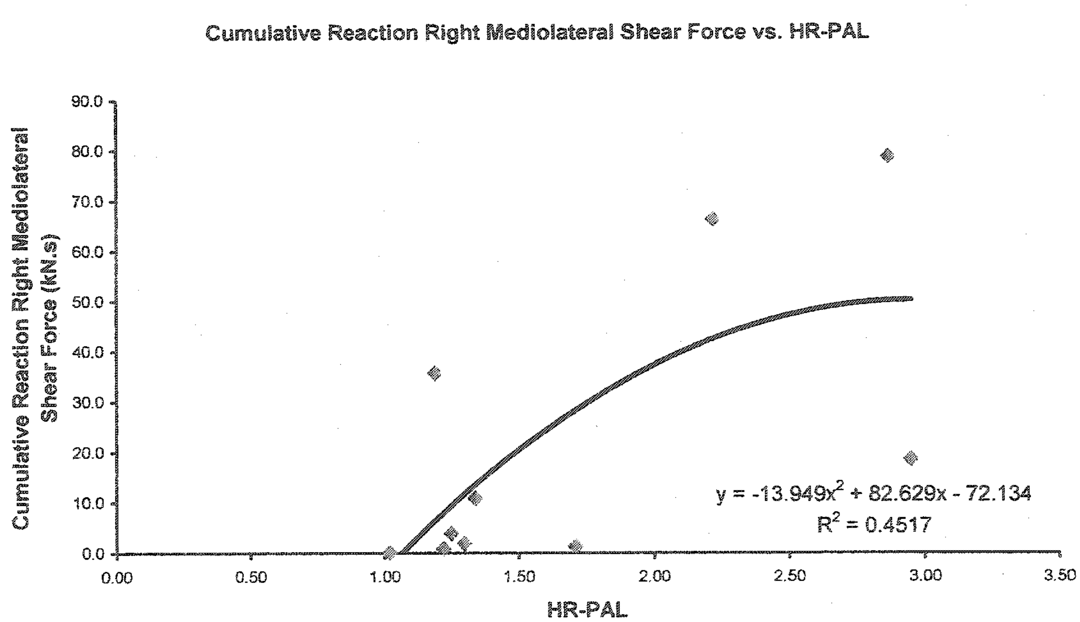
Cumulative Joint Anterior Shear Force vs. HR-PAL



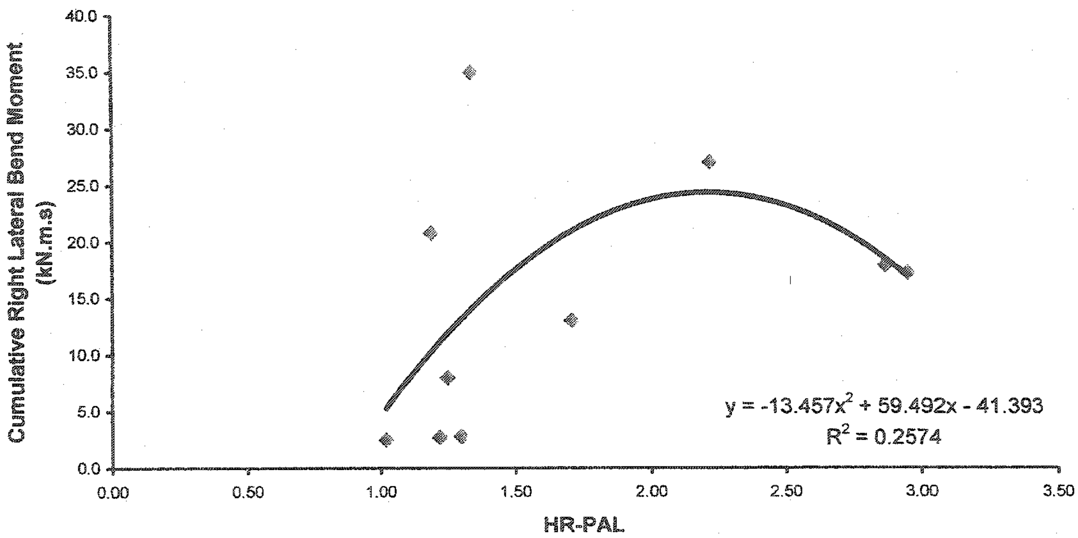
Cumulative Joint Posterior Shear Force vs. HR-PAL



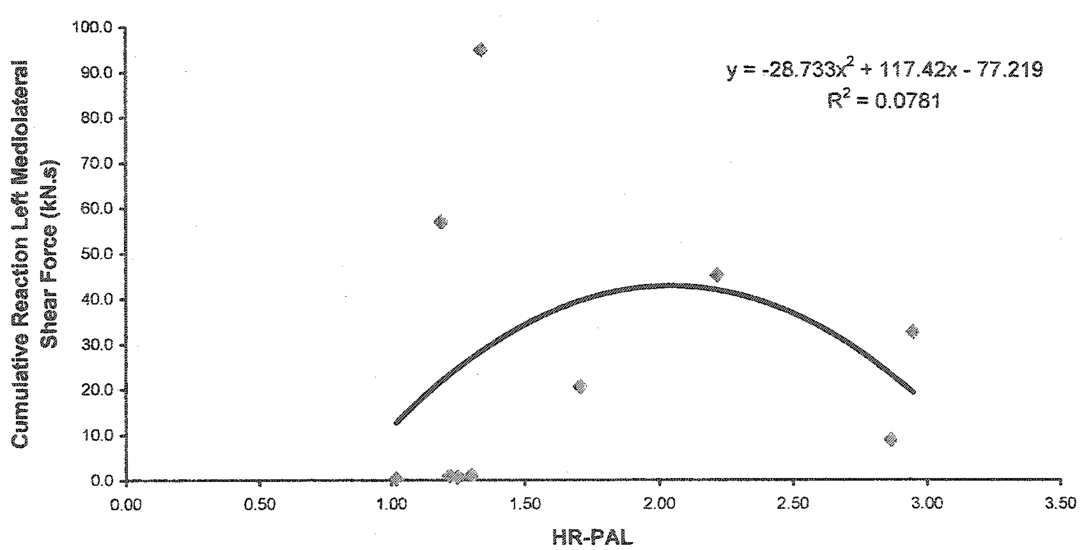

Cumulative Reaction Posterior Shear Force vs. HR-PAL
Cumulative Reaction Posterior Shear Force (kN.s)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
HR-PAL
y = -5.6217x2 + 33.874x - 32.833
R2 = 0.4472


Cumulative Reaction Right Mediolateral Shear Force vs. HR-PAL
Cumulative Reaction Right Mediolateral Shear Force (kN.s)
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
HR-PAL
y = -13.949x2 + 82.629x - 72.134
R2 = 0.4517

Cumulative Right Lateral Bend Moment vs. HR-PAL



Cumulative Reaction Left Mediolateral Shear Force vs. HR-PAL



VITA AUCTORIS

NAME:	Nadia Robyn Azar (*nee* Oglan)
PLACE OF BIRTH:	Windsor, Ontario, Canada
YEAR OF BIRTH:	1978
EDUCATION:	St. Anne's Roman Catholic High School Tecumseh, Ontario 1992-1997
	University of Windsor Windsor, Ontario 1997-2001 Bachelor of Human Kinetics
	University of Windsor Windsor, Ontario 2001-2003 Master of Human Kinetics