Effects of leg and back strength, and trunk isometric endurance on lifting coordination of females

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For my wife Vera

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ABSTRACT

The aim of this Master's thesis was to examine the effects of leg and back strength, and trunk isometric endurance on lifting movement patterns of females. Thirteen healthy females were recruited to participate in two consecutive sessions. Heart rate and whole-body kinematic, kinetic and electromyographic (EMG) data were recorded during lifting a 15 kg box from a floor level in series of bouts until exhaustion. The first and last bouts of the task were analyzed. Results show no significant change in lifting coordination with fatigue, mainly attributed to inter-individual variability in lifting techniques. We found significant relationships between measures of hip-back inter-joint coordination and of strength of the hips and the trunk. The greater the strength of these muscles, the more synchronized the hip-back inter-joint coordination. Since an asynchronous pattern has previously been associated with lifting-related injury risk, these results suggest that strength training may be beneficial in improving lifting performance and protecting the back from injuries.

ABRÉGÉ

Le but de ce projet de Maîtrise était d'examiner les effets de la force des jambes et du dos et de l'endurance isométrique du tronc sur les patrons de manutention chez les femmes. Nous avons enregistré les fréquences cardiaques, la cinématique, la cinétique et l'électromyographie (EMG) corporelles durant une tâche de manutention avec une charge de 15 kg soulevée du sol jusqu'à l'épuisement. La première et la dernière série de mouvements ont été analysées. Les résultats démontrent l'absence de changements de coordination avec la fatigue, que nous attribuons aux différences inter-individuelles de style de mouvements. Nous avons trouvé des corrélations significatives entre les mesures de coordination interarticulaire hanches-dos et de force des hanches et du tronc. Plus la force était élevée, plus la coordination était synchronisée. Puisque les études antérieures ont démontré des liens entre les patrons asynchrones et le risque de blessures en lien avec la manutention, ces résultats suggèrent que l'entrainement à la force pourrait entrainer une amélioration de la performance de manutention et une meilleure prévention des blessures au dos.

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INTRODUCTION

Back injuries cause suffering for the individual as well as financial expenses to the industry (McGill 2002). Canadian statistic data reveals that in 2003, lower back injuries were the second most common type of work related injury following hand injuries, with 16% of Canadians suffering a back injury in that year alone. Moreover, 70% of these back injuries were associated with lifting (National Research, Panel on Musculoskeletal et al. 2001). An association between a risk of low back injuries (LBI) and manual material handling (MMH) has been established (Hoogendoorn, Bongers et al. 2000, National Research, Panel on Musculoskeletal et al. 2001). A recent study from the North Carolina population showed that the prevalence of chronic lower back pain almost tripled during the period between 1992 and 2006, and that in both of these years, the prevalence was higher among females compared to males (Freburger, Holmes et al. 2009). Moreover, it appears that over the last three decades, the number of females in jobs with high physical workload has been increasing as opposed to a decreasing number of men occupying these positions (Torgén and Kilbom 2000). In jobs that involve lifting in particular, women have been found to have higher rates of LBI than men (Kraus, Schaffer et al. 1997).

Literature reviews based on industrial surveillance studies have informed of an increased risk of LBI among workers exposed to common lifting tasks (Bernard 1997). A clear link has been found between LBI and the loads imposed by manual material handling (MMH), frequent bending, twisting, physically heavy work and whole body vibration (Disorders, Workplace et al. 2001). Physical components of the task such as load magnitude, its origin height, lifting frequency and repetitive task duration have been identified as potential risk factors for MMH-related LBI (Marras 2008). Recent studies have focused their efforts on two specific aspect of the MMH-related LBI mechanism: 1) measurements of spinal loads imposed by these physical factors by using biomechanical analysis; 2) investigations of biomechanical implications caused by modifying these factors (Chaffin, Andersson et al. 2006, Marras 2008). However, due to the complex nature of the lifting task, it is difficult to precisely quantify an injury risk dose-response, so that the most effective preventative approaches remain poorly described.

One's lifting technique is considered one of the potential risk factors to LBI, and it appears that differences in lifting techniques lead to biomechanical changes that in turn may increase the risk of injury, or help avoiding it (Burgess-Limerick 2003). According to a recent review article (Burgess-Limerick 2003), typical lifting techniques have been identified according to the posture of a person the second he/she makes contact with the load and is ready to lift it. The two most common lifting techniques that have been described for lifting a load from a low height are the stoop posture, where the knees are almost fully extended and the spine flexes in order to reach the load, and the squat posture, where the knees flex and an erect posture of the trunk is being maintained. It has been found that when people lifted loads from low height in free style technique, they adopted various postures that were in between the stoop and the full squat (Burgess-Limerick, Abernethy et al. 1995, Burgess-Limerick and Abernethy 1997). It has been recommended to avoid adopting postures that create extreme lumbar flexion, which can usually occur in stoop lifting (McGill 2002, Adams, Burton et al. 2007, Marras 2008). However, although it has been suggested that the stoop posture is less mechanically advantageous and thus more risky, the direct link between these lifting techniques and injury risk is still not clear (Hsiang, Brogmus et al. 1997, van Dieën, Hoozemans et al. 1999).

For one thing, describing the lifting technique using only the initial posture adopted prior to the lifting movement fails to take into account the technique used throughout the movement, and this may explain the limitations in our understanding of the link between lifting technique and back injuries (Lindbeck and Kjellberg 2001). More detailed descriptions of the lifting technique take into account the movement coordination patterns during the performance of a single lift (Scholz 1993, Burgess-Limerick, Abernethy et al. 1995, Lindbeck and Kjellberg 2001). Movement patterns of a free-style lifting require a contemporaneous extension of the lower limbs and the trunk. However, the coordination between the joints is not simultaneous, and a pattern of a delay between the proximal and distal joints has been observed. Knee extension has been found typically to occur before hip extension, and hip extension in turn occurs prior to back extension. Greater delays between the joints suggest that movement pattern is more sequential, while smaller delays indicate that joints extend in a more synchronized manner (Burgess-Limerick 2006). Despite these advances, very few studies have used this more detailed approach to identify LBI risk related to MMH.

The majority of studies on the lifting technique have been conducted using male participants, and it is not clear if their results are also applicable to female workers. Not many studies exist in the literature that address the importance of movement patterns during a lift and there are even less studies regarding gender differences in these motion patterns (Scholz 1993, Lindbeck and Kjellberg 2001). Differences in movement coordination were found in a recent gender comparison study by Plamondon, Larivière et al. (2014), where men and women handled the same absolute load. Women exhibited movement patterns that positioned their spine in an excessive flexion and thus putting them in greater risk for LBI, however the reason for these differences are not clear. It has been recently found that leg and back strength influence the adopted lifting posture (Li and Zhang 2009). Therefore, strength differences in leg and back muscles between the genders might be the reason for these differences (Plamondon, Larivière et al. 2014). However, the exact factors underlying the obervations of lower lifting ability and greater MMH-related injury risk in females have yet to be precisely identified.

In summary, there are more women in the MMH workforce, and women report more LBI than men, however most studies on LBI have been conducted on men, and it is likely that MMH guidelines and ergonomics training material were also designed mainly according to male characteristics. Therefore, there is a need to better understand and be able to better describe lifting patterns of females, so as to develop more adequate injury prevention approaches.

LITTERATURE REVIEW

Risk factors for lifting-related back injuries

According to a review of epidemiological studies (Marras 2008), several physical, psychosocial and individual risk factors have been linked to Low Back Pain (LBP). Among the factors most commonly associated with higher risk of LBP, the individual factors of age, smoking and genetics, as well as individual psychosocial factors such as anxiety and depression have been cited. In addition, in 1988, the U.S. National Health Injury Survey reported that 65% of LBP and LBI compensation claims were attributed to occupational activities (Guo, Tanaka et al. 1995). According to the United States' National Institute for Occupational Safety and Health (NIOSH) Worker Health Chartbook (2000), the prevalence of LBP is greatest in some specific industries such as the service industry (28%), followed by the manufacturing sector (21%).

An extensive literature review of studies examining work-related factors and LBP has reported that there is a clear link between the loads imposed by manual material handling (MMH), frequent bending, twisting, physically heavy work and whole body vibration (Disorders, Workplace et al. 2001). Chaffin (1973) has previously found that workers dealing with heavy manual lifting had eight times the number of lower back injuries than workers carrying out sedentary types of jobs. Lifting frequency and repetitive work has also been directly linked to the prevalence of low back injuries (Karwowski and Marras 1999). In 1981, The National Institute of Occupational Safety and Health (NIOSH) found that one third of the United States' workforce was involved in what they defined as "excessive" manual handling work, and that this excessive lifting was the most significant cause of their low back injuries (NIOSH, 1981). They established four factors influencing the excessiveness of the lift and associated increased rate of injury: the mass of the object, its size, lifting frequency and the object's location relative to the lifter at the beginning of the lift (Health and Services 1981). However, in order to assess the exposure level of specific risk factors within the occupational environments, biomechanical assessments are required so as to quantify and provide precise metrics regarding the amount of exposure that induces the risk of injury.

Biomechanical analyses of the lifting task

The role of the biomechanical analysis of lifting is to help assess the internal loads imposed on spinal structures and tissues with a given external load (Marras 2008). Recent studies have emphasized the combined influence of the load magnitude and starting height on the external moments on the lumbar spine (Dolan, Earley et al. 1994, Marras, Parakkat et al. 2006). The spinal load increases when greater loads are lifted and when their origin height is lower, and the height origin factor has been found to have an even greater impact than mass on spinal loading (Hoozemans, Kingma et al. 2008). However, other studies suggest that the technique that people use to lift the weight also has an influence on the compression and shear forces on the spine (Potvin, McGill et al. 1991). During lifting, the trunk musculature and ligament forces act to handle the load, support the lower back and maintain the posture during the movement (McGill 2002). These authors suggest that a lifting technique that engages the muscles will consequently minimize the use of ligaments and their involvement in dealing with the imposed spinal loads. Since it is thought that ligamentous tissue injury is an important mechanism of LBI (McGill 1997), these studies suggest that paying attention to the lifting technique is crucial for reducing the moments on the lower back and avoiding overloading (McGill 2002).

Studies comparing stoop (i.e. knees are almost fully extended and the back flexes in order to reach the load) and squat (i.e. knees are almost fully flexed and back is straight) oriented lifting techniques in terms of spinal loading have found that shear forces and bending moments are generally lower in squat lifting, and if the load can be lifted from a position in between the two feet, the squat technique is associated with lower net moments (van Dieën, Hoozemans et al. 1999, Bazrgari, Shirazi-Adl et al. 2007). The proximity of the hands holding the load relatively to the body, the position of center of mass of the upper body and the lumbar spine curvature during the lift, all have a direct impact on the internal loads imposed on the spine (McGill 2002). Furthermore, adopting the fully flexed spine or close to its end range of motion posture during lifting increases the risk of back injury, and postures with extreme levels of spinal flexion should be avoided (McGill 1997, Burgess-Limerick 2003).

Despite this knowledge, describing the lifting technique using only the initial posture adopted prior to the lifting movement does not fully capture the technique used throughout the movement, and this may explain the limitations in our understanding of the link between the lifting technique and back injuries (Lindbeck and Kjellberg 2001). For this purpose, joint movement and coordination patterns during a full lifting cycle need to be analyzed, as well as their alterations in response to task related variables such as load's mass and its starting height, and an individual's inherent performance factors such as strength and endurance.

Lifting is a complex multi-joint task which involves motion at the ankle, knee, hip and the vertebral joints and inter-joint coordination, and the adaptation pattern to different conditions of the task plays an important role in describing this lifting technique (Burgess-Limerick, Abernethy et al. 1995). Inter-joint coordination is often assessed by quantifying the relative timing between two adjacent joints, with more simultaneous movements between adjacent joints being considered to be more synchronized and have a higher or stronger inter-joint coordination (Davis, Splittstoesser et al. 2003). Conventional methods of description of inter-joint coordination include angular position vs. time presentation (Burgess-Limerick, Abernethy et al. 1993). However, a recent and more accurate measure of multi-joint coordination is the relative phase angle (RPA) method (Burgess-Limerick, Abernethy et al. 1993). For every point in time during the lifting cycle, the relative excursion between two adjacent joints is calculated by subtracting the phase angle of the distal joint from the proximal joint at each point. Joint segments' movement is considered being fully in phase when the phase angle difference is 0°, i.e., the segments move simultaneously, whereas a difference of 180° indicates a fully out of phase movement and a sequential pattern of movement between joint segments (Plamondon, Larivière et al. 2014). Electromyography (EMG) provides other methods of measuring inter-joint coordination. EMG is a method used to record electrical activity in the muscles during contraction (Basmajian and De Luca 1985). Coordination of the knee, hip and the back during the full lifting cycle can be measured by quantifying the synchronization of EMG recordings of the accompanying muscular activity of the knee, hip and back extensors. Analyzing the plots of the associated EMG traces can provide a precise activation timing of each of the muscles relative to each other, through the period of lifting motion (Basmajian and De Luca 1985).

Davis, Splittstoesser et al. (2003) reported that when the adopted lifting posture at the onset of the lift was closer to the squat posture rather than the stoop one, the coordination between the knees, hips and the back increases (i.e. joint movements becomes more simultaneous). Furthermore, when a squat posture is adopted, inter-joint coordination increases even more as load's origin height is closer to the floor (Davis, Splittstoesser et al. 2003). In this study, these authors used 9.1 kg and 18.2 kg loads in five origin height positions: 0 cm, 19 cm, 38 cm, 57 cm, and 76 cm above the floor. It was found that those who adopted a squat posture when lifting from the lowest height position had the strongest, most simultaneous coordination between the knees, hips and trunk, and the lift resembled a synchronized whole-body movement. The adopted posture at the initiation of the lift is therefore an important factor affecting inter-joint coordination.

The weight of the load also has an impact on inter-joint coordination. Several studies investigated the effect of external load on the lifting coordination patterns during a sagittal lift from ground level height. Davis (1965) reported an increased trunk inclination along with a rapid hip raising movement when the weight was increased. Sholtz (1993) observed similar results among males in his study. While maintaining the same initial lifting posture, Schipplein (1990) found that subjects tended to change the joint moments by rapid knee extension when lifting heavier weights. When subjects' adopted posture at the start of the lift was in between the stoop and squat, a distal to proximal sequence of movement was later on documented by Burgess-Limerick (1993), meaning that knee extension lead hip extension and hip extension lead back extension. As the load weight increased however, this pattern of movement became more sequential (Burgess-Limerick, Abernethy et al. 1995). EMG measurements supported the findings described above, as peak activity of knee extensors on average occurred before peek activity in hip extensors, and increased load weight significantly delayed the peak activity of hamstrings, gluteus maximus and erector spinae (Burgess-Limerick, Abernethy et al. 1995).

A common finding from these studies was the alteration of a lifting technique that started as squat oriented with moderate spinal flexion, and as the load increased, that turned quickly into a full stoop lift, resulting from a decreased inter-joint coordination and consequently leading to an increased lumbar flexion. Burgess-Limerick (1995) suggested that the observed pattern which was naturally adopted by the subjects is thought to have functional consequences, since it reduces muscular effort. However, in both of these studies, the subjects had no experience in material handling. Therefore these findings may change with trained and experienced subjects who may have already optimized a learning effect.

Comparing patterns of novices to those of experts is a typical study design in relation to the biomechanics of lifting. Documenting the techniques used by experts could help understand optimal, injury risk-minimizing lifting techniques. In a study related to competitive sport performance, Escamilla (2000) studied the technique differences among low- and high-skilled lifters during the performance of a deadlift with heavy loads - a competitive version of a semi squat, which is executed by lifting a loaded barbell from the ground. Escamilla (2000) also observed the delay phenomena among low skilled lifters and described it as an excessive or premature extension of the knees, caused by the lifter's reduced ability to handle the external load. What began as a semi-squat lift turned into almost a stiff-legged version of the deadlift as a result of the premature extension of the knees, resembling a stoop lifting style and resulting in a more bent and round back. EMG measurements among the low-skilled lifters showed a decreased quadriceps activity and increased hamstring and erector spinae activity. On the other hand, highly skilled lifters indeed exerted more mechanical work than the low skilled, but they spared their back by maintaining a more coordinated lifting pattern and also succeeded in lifting heavier weights.

More recently, Plamondon et al. (2010) compared lifting techniques of manual handlers categorized as experts and novices. The experts not only had an extensive MMH experience but had low incidence of injuries in general and back injuries in particular during their working years. They were also identified as experts by their peers and managers. It was found that experts bent their knees more and flexed their spine less than the novices, thus keeping their spine less exposed to injury. These differences were even more notable when the load was lifted from ground level (Plamondon, Larivière et al. 2012). Studies highlighting strategies used by experts can also serve as models to implement in training and injury prevention approaches.

The above-mentioned studies investigated the effects of external conditions and expertise on a lifter's technique. Expertise is gained over several years of experience and the initial conditions of the lifting task, such as load's height and mass are not always in the handler's control. However, personal performance capabilities can be developed much quicker and are within the individual's control. Abernethy, Kippers et al. (2013) noted that with adequate practice and training, motor skills become more controlled, performance efficacy improves and the onset of fatigue is delayed. But what should be trained related to a specific task as lifting? Is it strength, endurance, conditioning and what specific muscles should be strengthened and conditioned? Are these factors able to improve one's coordination? It appears that indeed, individual performance factors such as strength, conditioning and endurance seem to influence the lifting strategy and its coordination (Trafimow, Schipplein et al. 1993). Leg and back strength have been established to be the limiting factors of one's lifting ability. It was found that weakness of either leg muscles or back muscles led to changes in the lifting strategy during the task (Zhang and Buhr 2002). Moreover, Li and Zhang (2009) found that a ratio between back and leg strength can influence on lifting strategy. Interestingly, subjects with stronger back than knees adopted a mostly more stoop oriented lift, and subjects with an inverse ratio used variable techniques. Furthermore, all of the subjects adopting the squat oriented strategy had more leg strength than back (Li and Zhang 2009). However, it is still not clear how back and leg strength influence not only the initial posture adopted prior the lift, but inter-joint coordination as well.

In an earlier study, Schipplein and Trafimov et al. (1990) found that when a squat oriented technique was adopted, quadriceps muscles were found to be a limiting factor and had an impact on inter-joint coordination. These authors studied the relationships between knee-hip and hip-trunk moments among inexperienced male subjects, using the method of increasing load in a sagittal lift from the ground. They provided evidence that although these patterns change due to the characteristics of an external load, they also depend on the subject's ability to execute this lift. An angular impulse was used as an indicator of muscular effort; it appeared that the knee extensors' effort remained constant in all load levels, up to the load of 100N. When the load's weight rose beyond 100N, subjects did not increase their quadriceps effort and thus had to exert more effort from the hip and back extensors. In order to do so, they extended the knees faster and by doing so, the hips rose quickly, the legs were straightened and the lifting technique turned into a stooped one, which increases lumbar flexion and may increase the risk of LBI (Schipplein, Trafimow et al.

1990). Therefore, knee extensor strength is an important factor that affects the way the load is lifted.

In conclusion, safe execution of the lift depends on the posture adopted at the onset of the lift, load's weight and inter-joint coordination during the lifting cycle. A more squat oriented lift seems to be adopted by the experts, and although safer for the spine, is limited by quadriceps strength which leads to more sequential inter-joint coordination as the load increases. However, the effect of hip extensor and back muscle strength on inter-joint coordination has not been studied. Therefore more research should be done to examine the effect of other muscles' strength on inter–joint coordination.

Fatigue's effect on coordination and its correlation to back injuries

A repetitive lifting motion, performed as part of a continuous and fatigue-inducing lifting task, even when lifting low weight loads, can lead to alterations in motor control and coordination patterns and thus increase the risk of back injury (Sparto, Parnianpour et al. 1997, McGill 2002). Fatigue (physiological fatigue) can affect the periphery (muscles) as well as central nervous system (CNS) components and is typically defined as an increased perception of the effort required to execute a task, resulting in inability to exert this effort (Enoka and Stuart 1992). Characteristics of local fatigue include decreased velocity and force of muscular contraction, shifts toward the lower spectrum in EMG frequencies and increased amplitude of EMG activity in a muscle (Enoka and Stuart 1992).

Dolan (1998) examined the effects of increased fatigue of erector spinae (L3-T10) on spine kinematics during a repetitive lifting task. A mixed group of subjects (6 males and 9 females) performed 100 lifts of 10 kg weight lifter's discs from the floor. The participants were allowed to use their preferred lifting technique and choose their own pace, as long as it could be maintained during the 100 lifts. EMG measurements were used to detect the fatigue-related changes in muscular activity. Lumbar flexion was measured before and after the task in terms of percentage of subject's maximal lumbar flexion. Participants' degree of lumbar flexion was 83% of fully flexed spine during the first five lifts and increased significantly to 90.4% during the last five lifts, which suggests that repetitive bending may lead to an alteration in spinal flexion. However, it is not clear what lifting posture was adopted by the participants and whether there were any changes in movement patterns of the lift during the task.

The effect of fatigue on multi-joint kinematics and coordination was also studied during a repetitive lifting test (Sparto, Parnianpour et al. 1997). Twelve male subjects lifted a small box attached to the robotic arm (25 cm length, 30 cm width, 23 cm depth, with handles centered along the length, 7 cm from the top) of a constant load set to 25% of subject's maximal isoinertial lifting ability. They were required to lift the load as fast as they could, using a freestyle lifting technique. The test stopped when the participant subjectively felt he could no longer continue or their heart rate reached 180 beats/minute. Fatigue was illustrated by an overall decrease of lifting force and power measured by a lifting simulator, which at the end of the test was reduced by 26% and 31% respectively. Mean lifting pace was four lifts/minute. The authors found a decreased knee and hip range of motion and an increased spinal flexion at the end of the task, and there was a significantly increased delay in the distal-to-proximal coordination of the hips and lumbar spine. It was suggested that these alterations in inter-joint coordination appeared as a result of an adaptation to the detrimental effects of fatigue or a loss of motor control (Sparto, Parnianpour et al. 1997). However, the relationship between coordination patterns and the adopted lifting posture is not clear. In addition, the fatigue protocol that was used in this study had the subjects lift at maximal rate; however it was up to the participants to determine their own subjective maximal pace. Consequently, each chosen rate could have been different and overall might not reflect the real conditions under which lifters work.

In another study (van Dieën, van der Burg et al. 1998), ten male participants lifted a barbell located on a motor-driven lifting device, using a self-chosen lifting strategy. The subjects were only required to lift the barbell, while the device lowered it. The barbell’s load was adjusted to 10% of their body weight, and they lifted it for 630 times during 9 bouts with 70 lifts within a bout. The pace was imposed by the lowering device, having the task last for 40 minutes. At the end of the task, decreased trunk extension velocity was found in most of the subjects which led to an increased phase delay between the hip and the trunk extension. Fatigue, however was assessed by subjective reports of the subjects. Authors suggested that the aforementioned alterations are due to the repetitive nature of the task, although they are not certain whether those findings are indeed mediated through back muscles’ fatigue. By looking into results in more details, it appears that among the ten participants, five adopted the squat posture as onset lifting posture during the first cycle, four used the stoop oriented posture and only one subject adopted the semi squat posture. It was observed that some of the subjects that started their lifts using squat oriented posture, changed it towards more stoop oriented one at the end of the task. However, it is not clear if the subjects first changed their posture and then there was a decrease in hip-trunk coordination or if it was the other way around. The interaction between the lifting's onset posture and the inter-joint coordination and their dual changes influenced by fatigue should therefore be further investigated.

With regards to personal physical abilities, one might presume that in a prolonged fatiguing task, the factor of muscular endurance also has an effect on coordination. Indeed, it appears that trunk flexors' and extensors' isometric endurance abilities are a better predictor of first occurrence of back disorders than isometric back strength (BIERING-SØRENSEN 1984, Jorgensen and Nicolaisen 1987). The role of trunk flexors, extensors and spinal lateral musculature in stabilizing the spine during various tasks including lifting was further investigated in a subsequent study on spinal stability (Cholewicki and McGill 1996). Results of this study suggest that spinal stability requires low to moderate but continuous coactivation of these muscles, in other words, a sufficient static endurance of these muscles is needed. However, what is unknown is how the endurance of these muscles affects inter-joint coordination during a repetitive and fatigue-inducing task.

In conclusion, fatigue causes alterations in lifting postures and decreases inter-joint coordination during a repetitive lifting task. As previously described, squat oriented postures have stronger inter-joint coordination and are safer in terms of reduced lumbar flexion, compared to lifting with a stoop posture. However, the link between the adopted posture at the start of the lift and the alterations in inter-joint coordination due to fatigue has not been fully studied. Moreover, most of these studies have been conducted on male participants, and little is known about whether both genders react similarly to repetitive lifting-related fatigue.

Sex/Gender (s/g) differences

Biological differences are well known to exist between males and females (Hooftman et al. 2009). The most often documented sex/gender differences (faced with the difficulty of distinguishing between both effects, we adopt this expression sex/gender (s/g)) between females and males are anthropometric and anatomical ones (Kettles, Cole et al. 2006). Anatomically, females have wider and more anteriorly tilted pelvis and greater lumbar lordosis than men (Norton, Sahrmann et al. 2004, Kettles, Cole et al. 2006). They also have more hyperextension of the knees, higher quadriceps angle (Q-angle) and consequently more hip adduction and internal rotation (Kettles, Cole et al. 2006). The Q-angle is composed by a line from the anterior superior iliac spine (ASIS) to the patella and a line from the tibial tubercle through to the center of the patella, and has been commonly considered to reflect the lateral pull of the quadriceps muscle (Oatis 2004). These anatomical differences might have an influence on the way women lift loads, since lifting is a compound movement involving the knees, hips and the lumbar spine. Females have higher spinal segmental flexibility and when compression forces are acting upon the spine, they provide greater intra-discal pressure in females than in males (Nachemson, Schultz et al. 1979). It was also found that females have lower spinal tolerance to compression forces (Jager and Luttmann 1991). The most commonly documented s/g physical difference is strength. On average, young adult female's muscle mass is 50% to 60% that of an adult male (Puhl, Brown et al. 1988). Females' lifting strength ranges between 40% and 73% of male lifting capacities (Marras, Davis et al. 2002). However, another study has shown that while trunk strength was larger in men, isometric back muscle endurance was higher in women (Biering-Sorensen 1984). In a supporting study it was found that type I fibers in lumbar extensor muscles were found in larger proportion in women than in men, and proportionally more type II fibers were found in men in comparison to women, which may explain the higher endurance capabilities of females' back muscles (Ng, Richardson et al. 1998). Despite the dramatic change in the labor market as females increasingly join the jobs characterized by high physical demands, the design of working conditions and requirements are rarely adjusted for women (Marras, Davis et al. 2003). Moreover, guidelines for lifting techniques do not include separate considerations for females (Albert, Wrigley et al. 2008). It appears that the majority of industrial lifting related studies were conducted with male volunteers, and it is not clear if their results can be assumed to be applicable to females as well (Lindbeck and Kjellberg 2001).

Recent s/g comparison studies examined biomechanical differences of spinal loading during lifting tasks (Marras, Davis et al. 2003). Under the same physical demands of the task (i.e. same absolute weight of the box and origin height), during the lifting motion, it was found that females applied more hip flexion when they bent to reach the load, whereas males comparatively showed more of a strategy of flexing their lumbar spine. Moreover, males had higher compression forces acting on their spine than females, and these differences increased with higher loads and lower height origins. However, since females have lower tolerance levels to spinal compression forces, and when their tolerance levels were compared with the measured compression forces, females were significantly closer to their tolerance limits than males. Women are therefore situated in higher risk of injury when performing tasks that are identical to those performed by men (Marras, Davis et al. 2003). In the same study the authors investigated the effect of weight (6.8 kg, 13.6 kg, and 22.7 kg) on the activity levels of spinal extensor muscles (erector spinae, latissimus dorsi, internal oblique). The erector spinae was mostly active during the lower weights; however, at 22.7 kg load, females significantly increased the activity levels of lattisimus dorsi, a secondary trunk extensor, with its activity levels rising almost to the same level as that of the erector spinae. EMG activity levels of these muscles were near 90% of the maximal voluntary contraction (MVC), suggesting that females were reaching their maximum strength limits.

Additional studies have also shown that females tend to adopt a more squat oriented technique in comparison to males, utilizing the hips and the knees more and thus maintaining low to moderate levels of lumbar flexion (Lindbeck and Kjellberg 2001, Davis 2003). As far as the method of lifting is concerned, these are good news since this method minimizes the risk of back injuries (Plamondon et al. 2010). However, the second parameter of the technique description, the performance, was not evaluated in that particular study and it is therefore not clear how the lift was performed in terms of inter-joint coordination. Other studies which investigated s/g differences in lifting coordination did not report the same differences as those described above (Albert 2008, Lindbeck 2001). In fact, Lindbeck (2001) found that females had a stronger hip-knee inter-joint coordination than males. However, since it was also found that females adopted a squat oriented method of lifting, which increases inter-joint coordination, and the fact that in both studies the loads' masses were only 7 kg – 8 kg for females and 12 kg – 13 kg for males may question how these findings can be compared to those of the studies cited above. Perhaps the weight was not challenging enough to reveal the potential physical and motor control abilities of the subjects. The authors have suggested that females should receive a separate attention regarding both experimental research, in designing appropriate workstations and conditions as well as training programs and technique related guidelines.

In a recent s/g comparison study, expert MMH male handlers and experienced female MMH handlers performed a lifting task, and biomechanical differences in lifting technique were examined (Plamondon, Larivière et al. 2014). According to recent ISO regulations (International Organization for 2003), the maximal limits for 99% of females and 95% of males are 15 kg and 25 kg respectively. In this study females were therefore asked to lift a 15 kg box, just like men, and as a result, females' personal physical abilities were challenged. These experienced female handlers indeed adopted the more squat oriented lifting posture at the beginning of lifting, like male experts did, and also brought the box closer to their body. Seemingly, excessive lumbar flexion should have been avoided by adopting this technique. However, a major sex difference was observed in the maximal amplitude of the RPA, with females showing significantly higher amplitudes than experts. Therefore, unlike male experts, the females performed the lift with what appeared to be a sequential inter-joint coordination; in other words, they rapidly extended their knees and continued the lift in a way resembling a stoop lifting technique and thus were likely as exposed to high risk of injury (Plamondon, Larivière et al. 2014). The reasons for these differences are not fully clear. The authors suggested that s/g strength differences might partially explain this; however, additional factors should be taken into consideration, since some females with lower strength than males did in fact adopt the same coordination pattern as male experts did (Plamondon, Larivière et al. 2014). Fatigue might be one of these factors and it was monitored in this study. Females were required to lift 96 boxes in a self-chosen pace, and after a 30 min break they lifted 48 more boxes in a self- chosen pace and additional 48 boxes in an imposed pace of 9 lifts/min. Females' fatigue was assessed by pre- and post-measurements of heart rate, Borg scale and EMG analysis of longissimus muscles. However, no significant differences were found in females' fatigue levels, and longer fatigue-inducing tasks might have produced different results (Plamondon, Larivière et al. 2012).

In summary, the literature agrees that a safe lifting technique depends on the adopted posture at the start of the lift and the inter-joint coordination of the knees, hips and the back through the lift. Utilizing a squat oriented posture and maintaining a strong inter-joint coordination, characterized by more simultaneous joint movements during the lift, presumably minimizes spinal loading, lumbar flexion and consequently the risk of injury. Inter-joint coordination is more simultaneous when initiating a lift in a squat-oriented posture, and becomes more sequential with increased load, fatigue or both. Quadriceps strength is a limiting factor that leads to less synchronized inter-joint coordination when its strength becomes lower than the load's weight. However, for many of these previous findings, it is not clear if they can be inferred to have the same effect on females. Fatigue affects inter-joint coordination; however the effect of fatigue on female's inter-joint coordination during lifting is not documented, and the link to the adopted lifting posture has not been studied either. The greatest detrimental impact of fatigue is inflicted on spine stabilizers - trunk flexors, extensors and lateral flexors. However, the isometric endurance of these muscles in women and its relationship with inter-joint coordination is unknown. The above coordination influencing factors were either observed among men and in few gender comparison studies, where the load and lifting origin were calculated to fit the anthropometric measures and strength abilities of women. It is therefore not clear if the results can be assumed to be applicable to females. Females are less strong and have a smaller spinal tolerance than men, which puts them at higher risk of injury. Females tend to adopt the squat oriented posture at the lift's onset as the male MMH experts do, however their inter-joint coordination is sequential through the lift, which increases the risk of injury even more. On the other hand, females have higher isometric endurance of trunk flexors and extensors. Since in realistic work settings, the load is not scaled to one's physical capabilities for both men and women, it is therefore of great importance to find if strength abilities of women are indeed an important factor for the difference in lifting coordination, and what, if any, is the role of each of the working muscles in the leg and back region and trunk endurance capabilities of contributing to lifting with more synchronized coordination.

The overall purpose of this study was therefore to determine the relationships between lifting coordination with leg lifting strength, back strength, and the isometric endurance of trunk's flexors, extensors among females. In addition, our aim was to examine the effects of fatigue on inter-joint coordination with respect to the initial lifting posture. In the current study we recruited female subjects to perform a series of muscle specific strength and endurance tests and a freestyle-lifting task under fatigue induced conditions. We hypothesized that females with greater leg and back strength and trunk endurance would display a more simultaneous inter-joint coordination during lifting and that inter-joint coordination would become more sequential due to fatigue.

RESEARCH ARTICLE

Effects of leg and back strength, and trunk isometric endurance on lifting coordination of females

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ABSTRACT

Sex/gender differences in manual material handling technique have previously been reported, although the exact origin of these differences is poorly understood. The goal of this study was to examine the relationships between muscle strength and endurance with inter-joint coordination of the knee-hip (KH) and hip-back (HB) during a lifting task performed until exhaustion. Thirteen healthy females were recruited to participate in two consecutive sessions. Isometric leg lifting strength, strength of both knee and back flexors and extensors, and back endurance were recorded during the first session. A lifting task using a 15 kg box was performed until exhaustion (Borg scale) a week later. Heart rate and whole-body kinematic, kinetic and electromyographic (EMG) data were recorded and the first and last bouts of the task were analyzed. Significant negative correlations were found between HB maximum relative phase angle (RPA) and leg lifting strength (r = -.805), knee extensor strength (r = -.705), knee flexor strength (r = -.633), back extensor strength (r = -.593) and back flexor strength (r = -.596). However, no significant relationships were found with endurance test performance. The greater the strength of these muscles, the more synchronized the hip-back inter-joint coordination. However, although the lifting task induced muscle fatigue measured by significant decreases in median frequency of back muscle EMG, there were no significant fatigue-induced changes in lifting coordination. Taken together, these findings suggest that increasing strength capacity (not endurance) of leg and back muscles may improve lifting performance by leading to more synchronized movement patterns. This in turn may have a protective role against overloading the back since an asynchronous pattern has previously been associated with lifting-related injury risk.

1. Introduction

Manual material handling (MMH) is considered a high-risk job in the industry in relation to lower back injuries (LBI) since it requires performing various lifting tasks through a working day (Plamondon, Denis et al. 2010). Indeed, a link has been suggested between LBI and the loads imposed by MMH (Musculoskeletal Disorders and the Workplace, 2001). Chaffin (1973) has previously found that workers dealing with heavy manual lifting had eight times the number of lower back injuries than workers carrying out sedentary types of jobs. Lifting frequency and repetitive work has also been linked to the prevalence of LBI (Karwowski and Marras 1999). The greatest risk for injury during heavy lifting occurs when the load is lifted from a low height, its distance from the body is great and the posture assumed is in flexed and asymmetric position (Musculoskeletal Disorders and the Workplace, 2001). It appears that differences in lifting techniques lead to biomechanical changes that in turn may increase the risk of injury, or help avoid it (Burgess-Limerick 2003).

The lifting technique has been defined in terms of the posture one adopts when the load is gripped before it is lifted (Burgess-Limerick, Abernethy et al. 1995). However, this definition has been found to provide limited meaning, and a more detailed definition of the technique should include the movement patterns during the performance of an entire lift from origin to destination (Scholz 1993, Lindbeck and Kjellberg 2001). A sufficient description of the lifting technique takes into consideration the motion at the knee, hip and vertebral joints and the inter-joint coordination between them, as well as the adopted posture at the onset of the lift (Burgess-Limerick 2003). Inter-joint coordination is often assessed by quantifying the relative movement between two adjacent joints (Burgess-Limerick, Abernethy et al. 1993, Davis, Splittstoesser et al. 2003).

Inter-joint coordination can be affected by the characteristics of the task which include the mass of the load, its size, height from the floor and finish height (Scholz 1993, Davis, Splittstoesser et al. 2003). It is also influenced by the adopted lifting posture (Burgess-Limerick 2003) and muscular fatigue (Trafimow, Schipplein et al. 1993). When subjects adopted a posture at the start of the lift that was in between the stoop and squat, a distal to proximal sequence of movement was documented by Burgess-Limerick (1993), meaning that knee extension lead hip extension and hip extension lead back extension. As the load weight increased however, this pattern of movement became more sequential (Burgess-Limerick, Abernethy et al. 1995). Fatigue induced by a repetitive lifting task, even when lifting low weight loads, can also lead to alterations in motor control and coordination patterns (Sparto, Parnianpour et al. 1997, McGill 2002). However the interaction between the lifting's onset posture and the inter-joint coordination and their dual changes influenced by fatigue is not fully understood.

The large majority of studies on lifting biomechanics have been conducted with male volunteers, and it is not clear if their results can be applicable to women as well (Lindbeck and Kjellberg 2001). Women in general are shorter than men, and having shorter segments can influence their lifting technique (Chaffin, Andersson et al. 2006). Women are also less strong than men and their lifting strength ranges between 40% and 73% of men lifting capacities, which means that for the same load women need to exert greater physical effort (Marras, Davis et al. 2002).

Sex/gender (s/g) differences in the adopted lifting postures were reported in several studies. Marras, Davis et al. (2003) indicated that females applied more hip flexion when they bent to reach the load, whereas males comparatively flexed their lumbar spine more. Under the same physical demands of the task, females were significantly closer to their spinal compression tolerance limits than males, so that females were situated in higher risk of injury (Marras, Davis et al. 2003).

Previous studies comparing male and female lifting have also shown s/g differences in inter-joint coordination. In a recent study, expert MMH male handlers and experienced female MMH handlers performed the same lifting task using a 15 kg box. No significant differences were found in fatigue levels after completion of the task. Both men and women adopted a squat oriented posture at the beginning of the lift. However, unlike men, women performed the lift with what appeared to be a sequential inter-joint coordination; in other words, they rapidly extended their knees and continued the lift in a way resembling a stoop lifting technique and thus were likely exposed to higher risk of injury (Plamondon, Larivière et al. 2014). The reasons for these differences are not fully clear. The authors suggested that strength differences in lower limbs and back between the genders may have an influence on inter-joint coordination and a longer fatigue-inducing task might have produced different results.

An extension of the previous study is therefore in place, and the aim of the current work is to examine the effect of leg and back muscle strength and fatigue on inter–joint coordination patterns among females, using both a challenging weight and a fatigue protocol to induce significant fatigue during the lifting task. We hypothesized that females with greater leg and back strength and trunk endurance would display a more simultaneous inter-joint coordination during lifting and that inter-joint coordination becomes more sequential due to fatigue.

2. Methods

The study was divided into two experimental sessions. The sessions were separated by at least 72 hours to avoid day-to-day fatigue or soreness effects. During the first session, physical capacity parameters were measured (strength and endurance) and the subjects were familiarized with the different experimental procedures. The second session specifically involved a task of fatigue induced by repetitive lifting of a 15 kg box.

2.1 Participants

A convenience sample of 13 healthy young females (mean age = 24.2 ± 3.4 years; mean height = 163.4 ± 5.5 cm; mean mass = 59 ± 8.4 kg) was recruited by the researchers from the institutional social network and through personal contacts to participate in this study. Subjects were excluded if they had previous experience in MMH, had any lower back pain or injuries, musculoskeletal or cardiovascular impairment or diagnosed condition that could affect their performance of the experiment. The study was performed at the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) in Montreal, Quebec. At arrival, subjects provided written informed consent prior to participation by signing forms approved by the Research Ethics Board of the Centre for Interdisciplinary Research in Rehabilitation (CRIR) of Greater Montreal.

2.2 Measuring systems

Two photogrammetric measuring systems were used to record the tridimensional (3D) co-ordinates of markers attached to the body segments. 12 rigid clusters of markers are attached to each of the

following segments: head (1); back at C7 (1); T12 (1) and S1 (1); both arms (2); both forearms (2); both thighs (2); and both feet (2).
The first system consisted of infrared LED whose signals were collected by four Optotrak© columns (Northern Digital Inc., Waterloo, Ontario). The Optotrak system's sampling frequency was set at 30 Hz, and the markers' 3D reconstruction error is generally less than 1 mm (Plamondon, Denis et al. 2010). Since this system does not generate video images, a second system consisting of three video cameras allowed verification of the Optotrak system's qualitative data (both systems were aligned on the same global reference system) for corrections of some missing data, and ergonomic analysis (not included in this article) of the handling tasks. The external forces applied by the feet on the floor during the handling tasks were obtained by using a large in-house-designed force platform (1.90 m x 1.30 m) mounted on 6 AMTI mini platforms (model MC3A-6-1000, Watertown, Massachusetts). This type of platform was designed to allow subjects to do MMH tasks without foot movement constraints and has been validated (Desjardins and Gagnon 2001). A home made synchronization system was used to synchronize all instruments (Optotrak, video and force platform).

EMG was recorded at 1024 Hz with pre-amplified bipolar electrodes (gain: 1000, model DE-2.3, Delsys, Boston, MA) placed bilaterally over biceps femoris (BF), vastus lateralis (VL), gluteus maximus (GM) and erector spinae (ES). ES electrodes were placed over the longissimus muscle, 3 cm lateral to spinal process of L3. For VL, the electrodes were placed at the middle of the line from the greater trochanter and lateral femoral epicondyle. BF electrodes were placed in the middle of the line between the ischial tuberosity and the lateral epicondyle of the tibia. For GM the electrodes were placed in the middle of the line between the sacral vertebrae and the greater

trochanter (Hermens et al., 1999). A reference electrode was placed on the middle of the tibia. Before placing the electrodes, the skin was cleaned with alcohol and shaved for better signal transmission.
Heart rate (HR) was monitored with a Polar system (model RS800; www.polar.fi).

2.3 Physical capacity

On this first session the following physical tests were performed: general test of isometric maximal lifting strength (MLS), isometric maximal knee extension (MKE) and knee flexion tests (MKF), maximal isometric back extension (MBE) and back flexion (MBF) tests and isometric endurance of trunk extensors (ETE) and flexors (ETF). The order of the tests was randomized. The MLS test was performed as the subject was standing in half squat position of 120º of knee flexion (180° being the full extension) positioned to grasp a handle at knee height (Fig. 1).

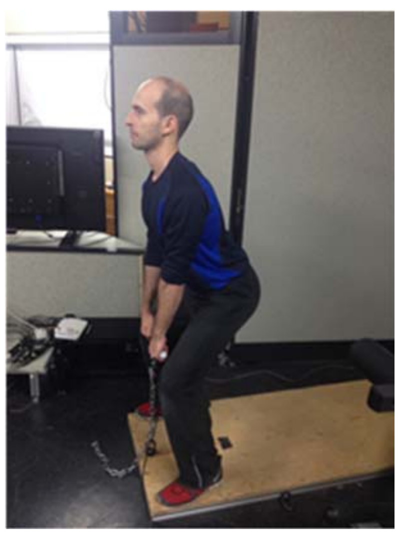


Fig. 1. Illustration of general lifting strength test.

The subject then exerted maximal extension force against a load cell fixed to the floor, maintaining a static position (Chaffin, Herrin et al.

1978, Chaffin, Andersson et al. 2006). The MKE test was performed on a designated knee flexion/extension bench (Fig. 2).

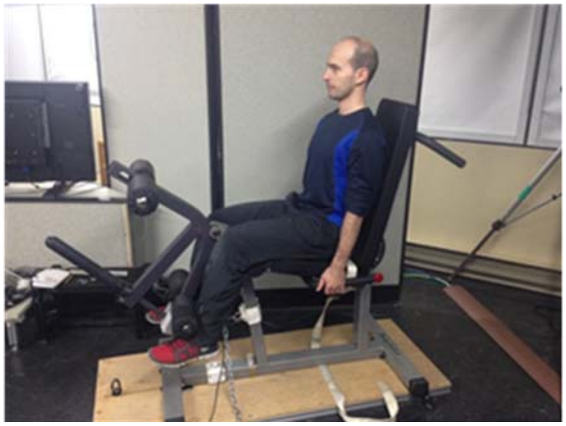


Fig. 2. Illustration of knee extension test.

The subject was seated, positioned with 90° flexion at the knee, hands holding the handles. The subject then exerted a maximal extension force at the knee. The MKF test was performed with the subject lying prone on the designated bench, positioned with 90° of flexion at the knee (Fig. 3).

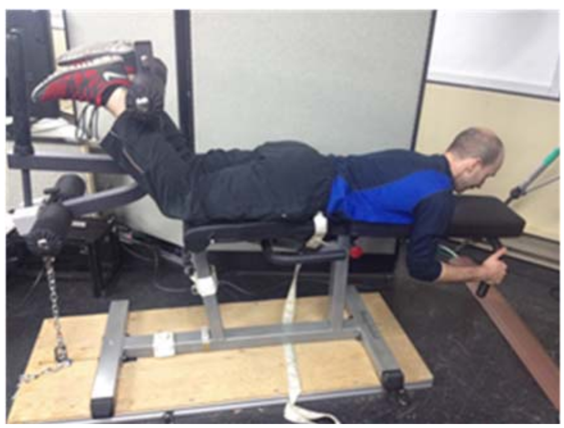


Fig. 3. Illustration of knee flexion test.

The subject then exerted a maximal flexion force at the knee. These tests began with two warm up attempts, 50% and 80% exertion with 30 seconds rest in between. After one minute of rest, three maximal attempts of each test were performed with three minutes of rest between each attempt and the highest result was taken. The subjects were instructed gradually exert the force, and hold for three seconds when reaching their maximal output. MBE and MBF tests were performed with the subject placed upright in a dynamometer (Fig. 4) and the pelvis stabilized (Larivière, Gagnon et al. 2001).

Fig. 4. Illustration of back extension/flexion strength and endurance extension testing using a dynamometer.

The subject exerted maximal effort in extension for six seconds and maximal flexion test followed right after. Each test was performed three times with three minutes of rest in between the extension/flexion cycles.

The ETE test was also measured using the dynamometer with the same placement of the subject. The test consisted in exerting an isometric extension force equal to 50% of the previously measured maximum back extension strength to exhaustion (Reeves, Cholewicki et al. 2006).

ETF was measured using the V-sit test (McGill, Belore et al. 2010). The subject was positioned in a sit-up position, with her back rested on a jig at 60^{o} from the floor. Both knees and hips were flexed 90^{o}, the arms were folded across the chest with the hands placed on the opposite shoulder and the toes were secured by the experimenter (Fig. 5).At the beginning, the jig was pulled 4 cm backwards and the subject tried to maintain the static posture until exhaustion, or until her back touched the jig (McGill, Childs et al. 1999, McGill, Belore et al. 2010).

Fig. 5. Illustration of trunks' flexors endurance test.

Familiarization with lifting experimental procedures followed physical capacity tests. The subject was presented with a metronome, and was asked to lift 5 kg box three times, 15 kg box for three times. Finally, the subject was offered to try lifting a 23 kg box is she wanted to. The subject had the chance to lift the 23 kg box up to three times.
During the familiarization session, no lifting technique was ever demonstrated to the participants and no comments were given about the technique they used.

2.4 Lifting task

On this second session, the lifting task was performed by the participants. The lifting task consisted in lifting a 15-kg box with no handles (26 cm deep x 35 cm wide x 32 cm high) using a custom made two pallet lifting device (Fig 6.). Subjects had to lift the box from the lower pallet in the sagittal plane, put it on the upper pallet approximately at waist height (see below) and lower it back.

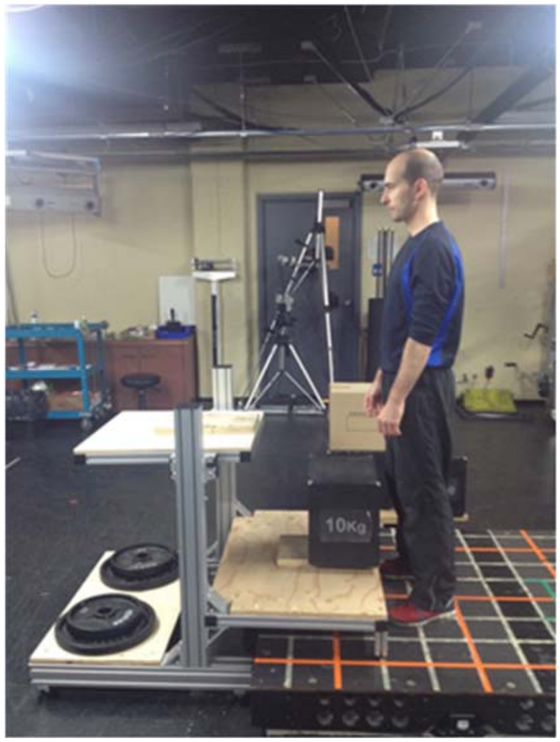


Fig. 6. Illustration of the experimental set-up during the lifting task.

The bottom height of the box from the force platform was 16.5 cm, and this height from the ground was kept constant for all subjects. The height of the upper pallet and the horizontal distance from the subject were adjusted for each subject. This was done by placing a box on top of the upper pallet, and having the subject stand in her lifting position, facing the platform with her shoulders at neutral position and elbows flexed 90^{o}. The upper pallet vertical position was then adjusted so that the height of subject's hands matched the top of the box (Fig. 7). The upper pallet's horizontal position was adjusted when the subject is at his lifting position, bending down. The distance was adjusted in a way that in case of bending during the lifting, the subject's head would not come in contact with the upper pallet (Fig. 8).

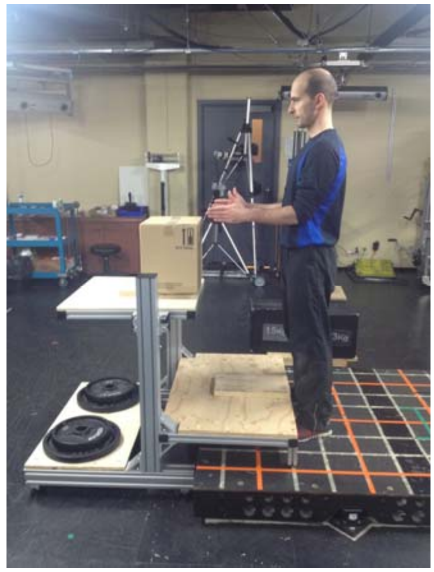


Fig. 7. Illustration of upper pallet vertical adjustment.

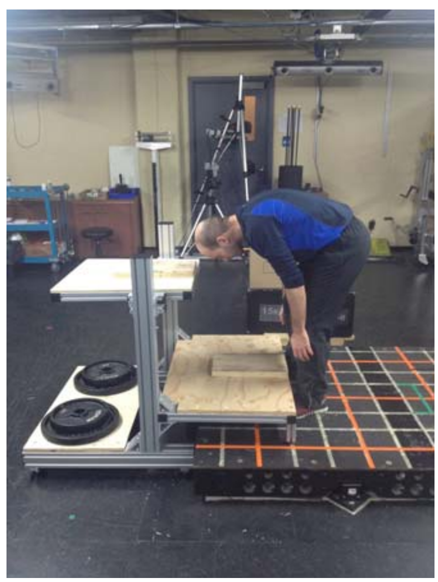


Fig. 8. Illustration of upper pallet horizontal adjustment.

2.4.1 Task description

The task was composed of bouts, 10 lifts within each bout. The lift was performed at an imposed lifting pace of nine boxes per minute, selected to induce fatigue (Garg and Saxena, 1979). After completion of each bout, the subject was asked to stop and rate the difficulty of the task using the general Borg rating scale of perceived exertion (Borg 1970). The task ended when the subject was either unable to continue or her rated score was at least 17 on the general scale, indicating a state of very hard perceived exertion. The subjects were unaware of this stoppage criterion. The subjects were instructed to maintain their feet position on the force platform without contact with the lower platform and move them as little as possible. The complete description of the MMH task is as follows: on the second beat of the metronome, the subject started the lifting task from an upright position facing the pallet. The box was located on the lower pallet, and the subject lifted the box by grasping it with both hands under each side and putting the box on the upper pallet. The subject then returned to an upright position, and then grasped the box again, lowered it to the lower pallet and returned to an upright position once again. At the sound of the next beat of the metronome, the subject began the next lift, while the experimenter was counting the number of the lift out loud. After the 10^{th} lift, the subject was instructed to stop and rate her perceived exertion right away. If the rating was lower than 17, the subject was immediately instructed to continue lifting another 10 lifts starting on the next beat of the metronome. Subjects were instructed to lift faster, if they were too slow.

2.4.2 Experimental procedure

At the beginning of this session, the participants were dressed appropriately to put on the EMG electrodes and HR bracelet and to install the clusters of markers. Following this, the subject performed a warm up lifting task with a metronome, which imposed a pace of 9 lifts per minute. The warm up included lifting 5 kg box three times, followed by lifting 15 kg box for three times. Finally, if the subject lifted a 23 kg box during the first session, she was asked to lift this box the same amount of repetitions as she did on the first session (i.e. up to 3 lifts). The subject was then given a rest of five minutes if she lifted a 23 kg box during warm up, and three minutes otherwise. After the rest, the subject was asked to rate her level of perceived exertion on the Borg scale. Three more minutes of rest were given if the Borg rating was higher than 8, otherwise the subject proceeded with the protocol. Next, right before the onset of the lifting task the subject completed two sub-maximal isometric tests (EMG Pre-tests) to evaluate localized muscular fatigue of the ES, GM, BF and VL muscles. The submaximal tests consisted in holding the trunk in a horizontal position for 5 s while lying prone on a Roman chair and holding a half squat position for 5 s (120^{o} knee flexion) while standing (Fig 9, Fig 10).

Fig. 9. Illustration of ES, GM and BF fatigue EMG testing position.

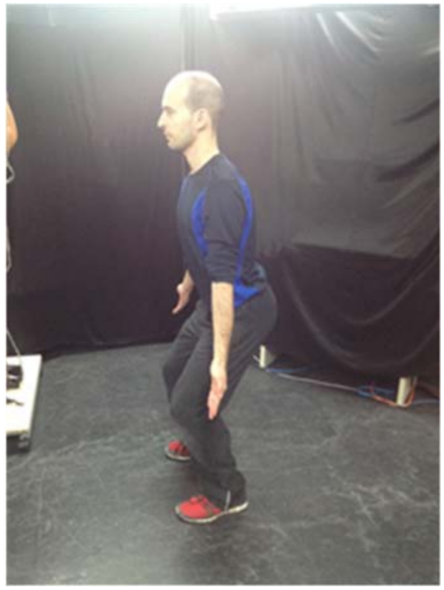


Fig. 10. Illustration of VL fatigue EMG testing position.

Then, the subject was asked to perform the imposed-pace lifting task of the 15 kg box. Right after completing the lifting task, the subject repeated the two submaximal isometric tests (EMG Post-test).

2.5 Data analysis

Dynamic 3D linked-segment model was used to estimate the net moments at L5/S1. This model calculates the net moments on the basis of external forces, the kinematics of body segments, and anthropometric data. The segment parameters were estimated by means of Jensen's elliptical method (1978). External forces on the feet were collected from the force platform. All of these input data were then integrated into the segment model to calculate the net moments at L5/ S1 expressed in the coordinate system of the pelvis (flexion extension, lateral bending and torsion moments) using the equations of Hof (1992) (see also Plamondon et al., 1996; Kingma et al., 2006). With the subject in the anatomical position, the longitudinal axis is upward, the sagittal axis is forward and the transverse axis is to the left. The Grood and Suntay (1983) method was used to estimate 3D angular motion. The flexion/extension rotation is about the transverse axis of the pelvis (proximal segment), the torsion rotation is about the longitudinal axis of the trunk (distal segment), and the lateral bending rotation is about the floating axis normal to the two preceding axes. The magnitude of the EMG signal was measured with a Root Mean Square (RMS) method with a moving average window of 100 ms. Median frequency (MF) of the EMG power spectrum was computed using the middle 3 s of the 5 s EMG signal period captured during the submaximal isometric contractions. Each single lift was broken down into two phases: lifting phase and a deposit phase. The lifting phase included a pre-lift (gripping), where the subjects bent into the initial lifting posture and gripped the box and the actual lifting of the box from the lower pallet. The deposit phase is the placement of the box on the upper pallet. The duration time of each lift (meaning the time which the weight of the box was supported by the subject) was divided into two equal sections (time/2), such that the first section was an integral part of the lift and the second an integral part of the deposit (Plamondon, Delisle et al. 2014). T1 is the time the subjects begins to grip the box. T2 is the beginning of the lifting phase. T3 is the time when the box is deposited on the pallet. T6 is exactly 50% of the time period between T2 and T3 and it indicates the end of lifting phase and the beginning of the deposit phase. Only the lifting phase was analyzed in our study.

2.5.1. Dependent fatigue variables

Fatigue was estimated by means of EMG (localized ES, GM, BF and VL fatigue), HR and Borg scale ratings. The mean HR and the mean normalized HR were calculated for the last bout of the lifts (%HR = HR/HR_{max}; HR_{max} = (220-age); ACSM, 2010). EMG fatigue includes MF values of the right and left ES, GM, BF and VL muscles for the pre and post EMG tests. Borg scale ratings were obtained before each EMG test and after each bout of lifting.

2.5.2. Dependent biomechanical variables

Peak values were calculated during lifting for the resultant moment at L5/S1 (i.e., the vector sum of the three moment components). Also, at the instant of the peak resultant moment the following were calculated: occurrence of the peak resultant moment, lumbar flexion angle, trunk inclination (trunk flexion angle from the vertical calculated from the local coordinate system at T12), and the right and left knee flexion angles.

2.5.3. Inter-joint coordination variables

Inter-joint coordination, as assessed using relative phase angle (RPA) analyses (Burgess-Limerick et al., 1993, 1995; Albert et al., 2008), was studied during the lifting phase of the box. Relative phase can be defined as the relationship of the movement and relative timing between adjacent joint pairs (Albert et al., 2008). Relative phase variables were estimated between knee and hip (K-H; right and left), and between hip (right and left) and back (H-B). The method used was the one described in Burgess-Limerick et al. (1993). Only the rotation in the sagittal plane (in the flexion-extension plane) was considered here. RPAs were calculated by subtracting the phase angle of the distal joint from the phase angle of the proximal joint at each normalized time point. A difference of 0° indicates that the two segments are moving perfectly in phase whereas a difference of 180° indicates that the segments are perfectly out of phase. In our convention, a positive phase value indicates that in the knee-hip joints the knee joint is leading the motion of the hip joint, while a negative relative phase value indicates that the hip joint is moving ahead of the knee joint. Maximum and minimum values of relative phase between joints were calculated.

2.6 Statistical analysis

Leg strength, back strength, spinal flexors, extensors isometric endurance variables and their effect on inter-joint coordination variables were tested by individual Pearson correlation coefficients analyses.

The effect of fatigue on lifting coordination was assessed by computing the differences in kinematic parameters between the first and the last lifting bouts (10 lifts each bout), using paired t-Tests ($p < 0.05$).

3. Results

3.1. Physical Capacity

Individual variation in physical capacity tests is presented in Fig. 11 and Fig. 12. Leg lifting strength was observed to produce the highest values among the lower limb strength tests. Knee extension strength was greater than that of the knee flexion. Back extension strength was observed to be higher than back flexion. Table 1 summarizes the mean values.

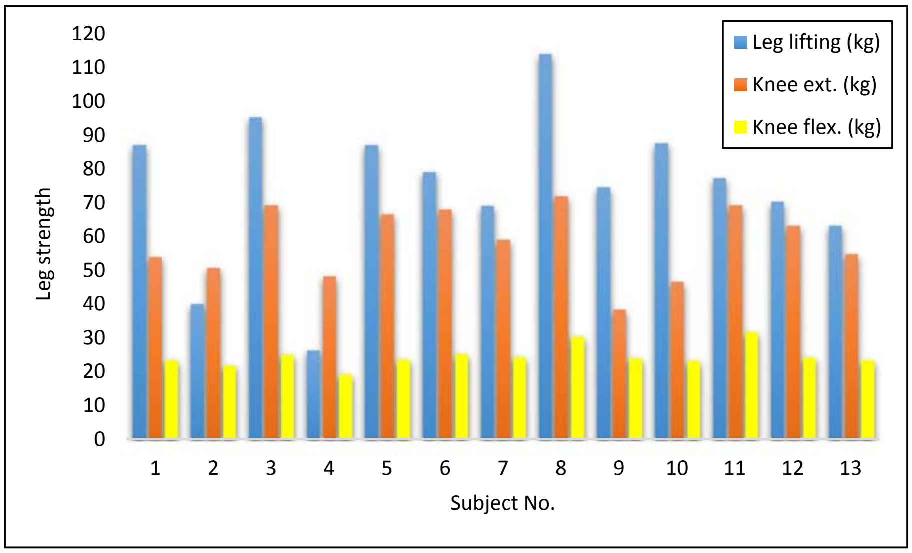


Fig. 11. Illustration of variation in leg strength tests performed by the 13 subjects.

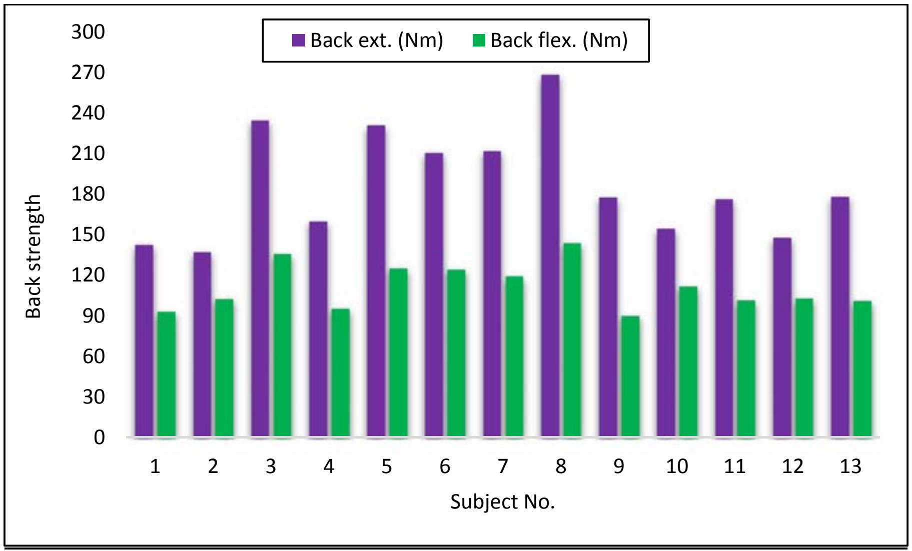


Fig. 12. Illustration of variation in back strength tests performed by the 13 subjects.

Table 1

Mean values (M) and standard deviation (SD) for Physical capacity tests.

Variables	M (SD)
Leg lifting strength (kg)	74.7 (22.7)
Back extension strength (Nm)	187.1 (40.9)
Back flexion strength (Nm)	113.4 (16.4)
Knee extension strength (kg)	58.5 (10.6)
Knee flexion strength (kg)	24.6 (3.3)
Back extensors endurance (min)	2.6 (1.3)
Back flexors endurance (min)	4.9 (2.0)

3.2. Kinematics of the lifting technique

Initial posture at the onset of the lift is depicted below by the level of knee flexion during the first bout of lifting, and shows variation between subjects. Most of the subjects assumed a posture between a stoop and a squat, which is characterized by knee flexion between 45°-80° (0° = full knee extension, +90° = full knee flexion) (Fig. 13).

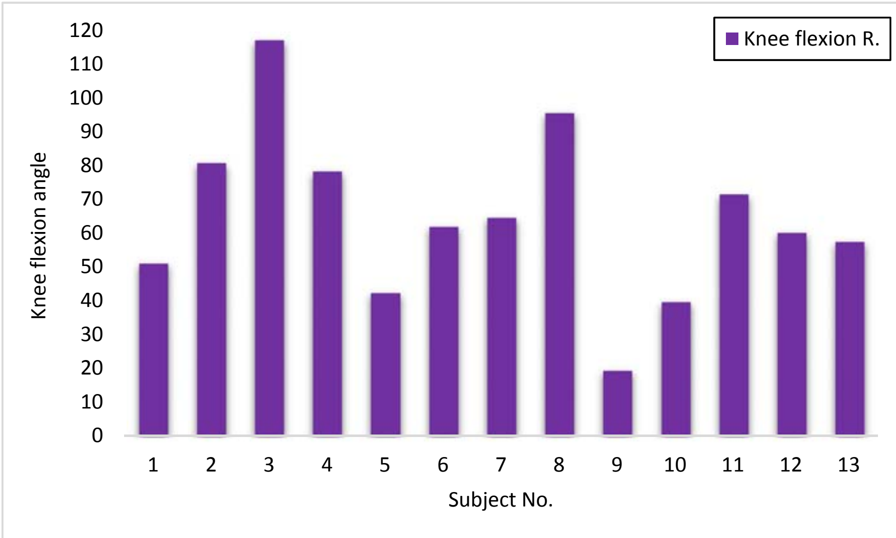


Fig. 13. Illustration of variation in the posture assume by the subjects at the onset of the lift during the first bout.

Notes: R. = Right

An in depth video analysis was made to provide a qualitative classification of lifting techniques. This classification divides lifting technique into two parameters: posture adopted at the start of the lift and a pattern of inter-joint coordination (Burgess-Limerick 2003). Initial lifting posture was classified into three categories: Squat - knees flexion around 90° or more; Stoop - minimal knees flexion 0° to 20 °; Semi-squat –moderate knees flexion, between 20° and 80° (Plamondon, Larivière et al. 2014). The majority of the subjects adopted the semi-squat posture at the beginning of the lift (Fig. 14).

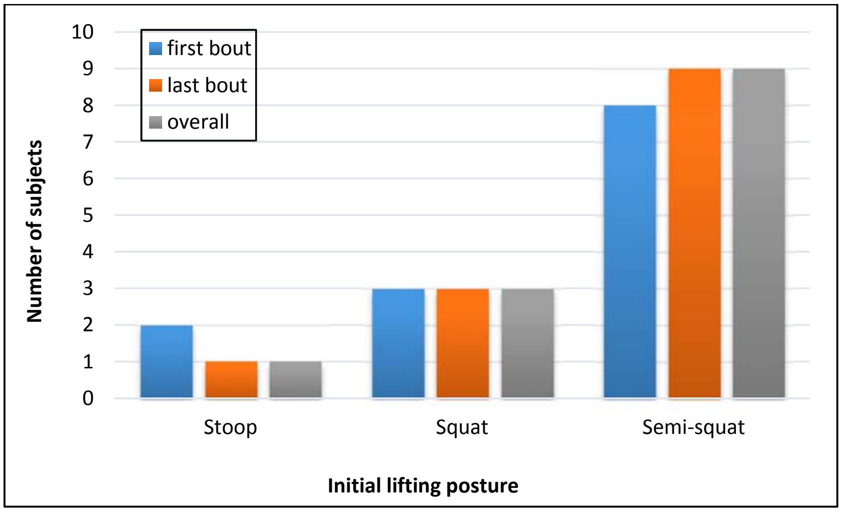


Fig. 14. Initial posture adopted at the onset of a lift among 13 subjects.

The peak L5/S1 resultant moment occurred slightly after the beginning of the lift, on average at 16% of the entire lift time (Table 2).

Table 2

Mean values (M) and standard deviation (SD) for kinematic values at the occurrence of peak L5/S1 resultant moment during the first bout.

Variables	M (SD)
Occurrence (%)	16.3 (6.7)
Lumbar flexion angle (°)	56.1 (14.6)
Trunk inclination (°)	85.0 (13.0)
Right knee flexion angle (°)	46.6 (21.7)

Notes: Occurrence (%) = Occurrence of resultant moment: negative value = pre-gripping phase; 0 to 50% = lifting phase.

Corresponding angles of knee flexion, lumbar flexion and trunk inclination represent the variation in lifting styles between the subjects during the first bout of lifting (Fig. 15).

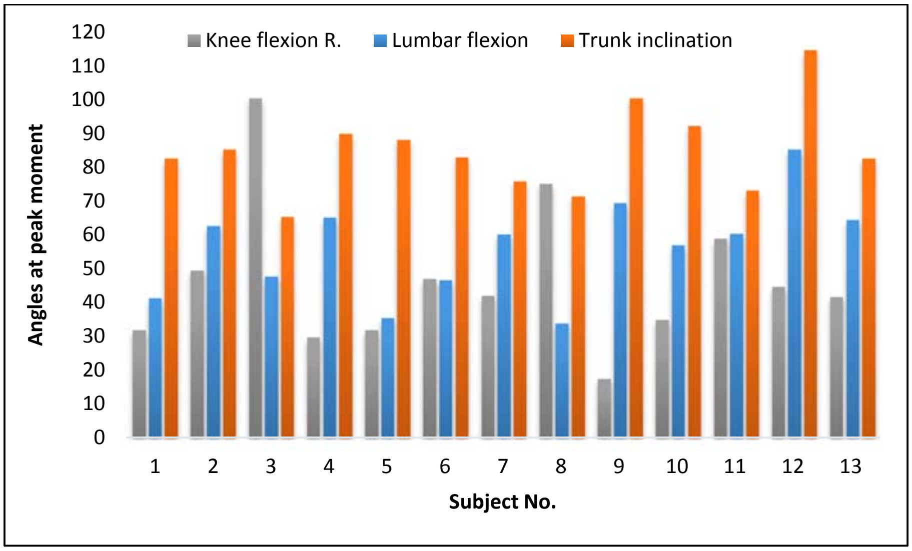


Fig. 15. Illustration of variation in knee flexion, lumbar flexion and trunk inclination at the occurrence of peak L5/S1 moment, during the first lifting bout (average of 10 lifts).

Movement patterns of a lift were classified into four categories: Stoop – initial posture is stoop, there is a minimal knee flexion and the lift is executed by the back extension; Synchronized - initial posture is squat or semi-squat, knees, hip and back extension is simultaneous; Sequential - Initial posture is squat or semi-squat, once knee extension is almost completed, it is immediately followed by back extension. When back extension starts, the box is generally lower or at the level of the pelvis; Hybrid - initial posture is squat or semi-squat, knee extension starts first then followed by back extension. The sequence is less evident but knee extension is completed before that of the back. There is still at least 45° back extension left when knee extension is completed. Box position is lower than in a synchronized pattern when back extension is executed (Plamondon, Larivière et al. 2014) (Fig. 16).

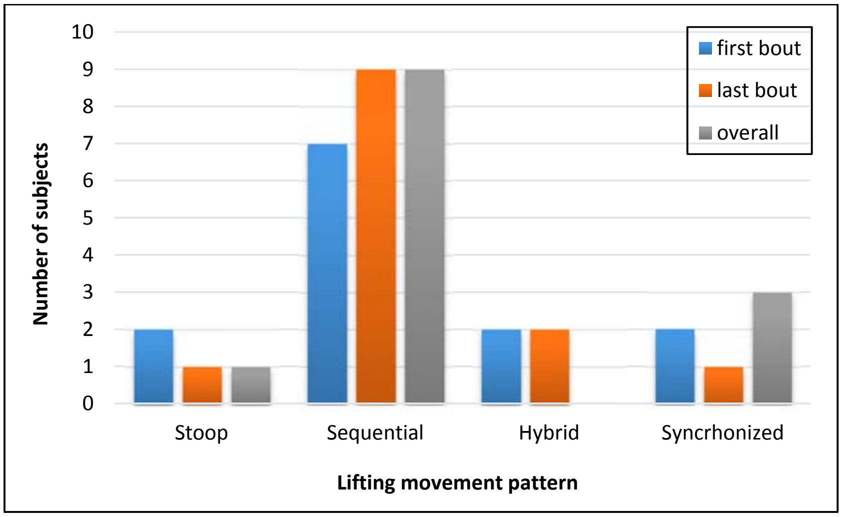
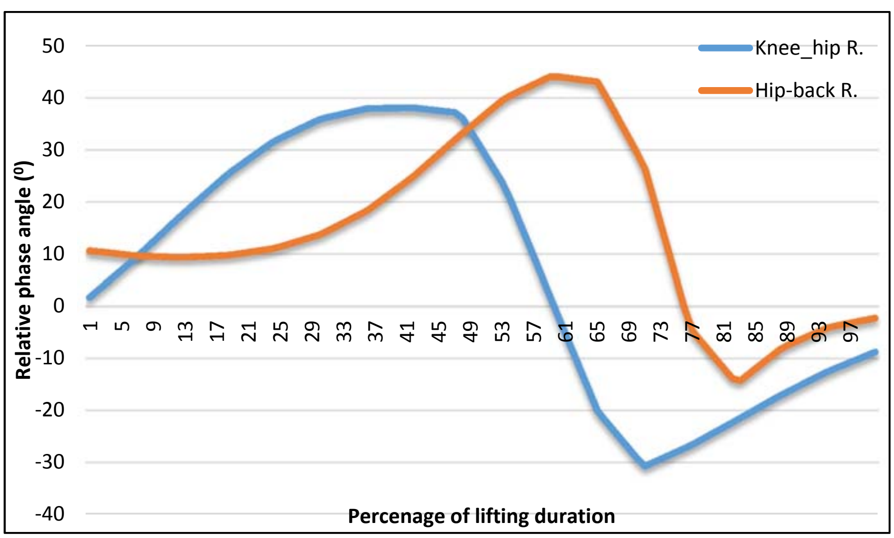


Fig. 16. Movement patterns through the lift among 13 subjects.

3.3. Inter-joint Coordination

Both qualitative and quantitative analysis of lifting technique showed that 8 out 9 subjects who adopted the semi-squat technique exhibited a sequential movement pattern (Fig. 17a), while 2 of the 3 subjects who adopted the squat technique exhibited a synchronized pattern of movement (Fig. 17b).

a



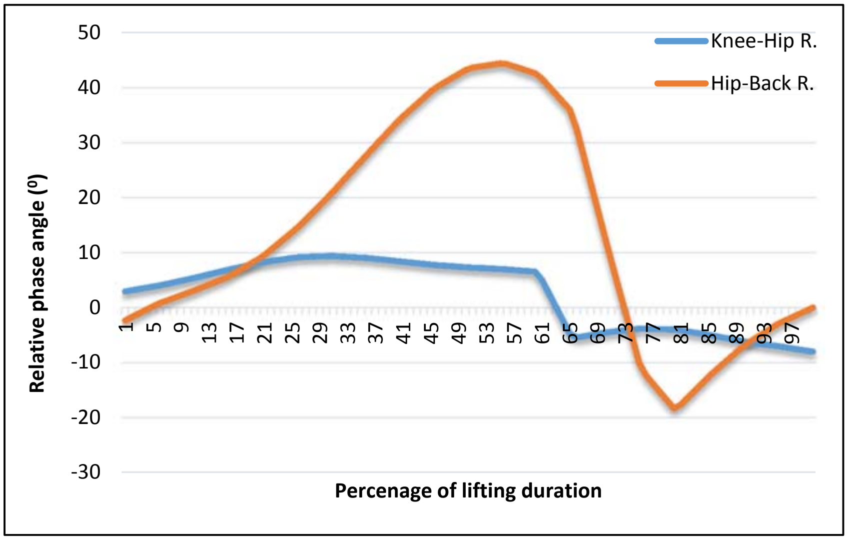
b 

Fig. 17. a) Semi-squat posture with sequential movement pattern, one representative trial. b) Squat adopted posture with synchronized pattern of movement, one representative trial.

Maximum RPA between the K-H and the H-B were all found positive, meaning that the knee was leading the hip and the hip was leading the back (Fig. 18).

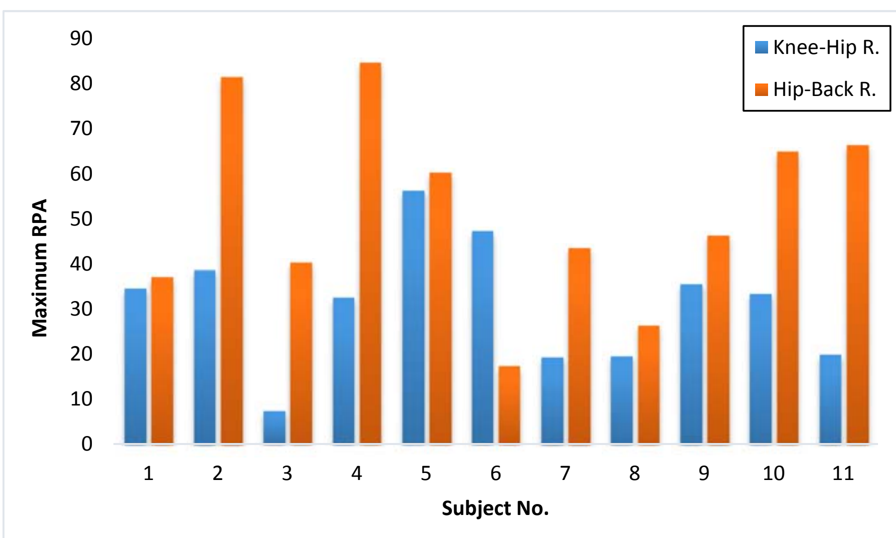


Fig. 18. Illustration of variation in inter joint coordination at the K-H and H-B.

Notes: R. = Right

Two subjects were excluded from inter-joint coordination analysis as they were exhibiting a pure stoop lifting style, which consisted of only back extension. Table 3 summarizes the mean values of the maximum RPA during the first lifting bout.

Table 3

Mean values (M) and standard deviation (SD) for the maximum RPA values during the first bout.

Inter-joint	Variables	M (SD)
Knee-Hip Right	Max RPA (°)	34.1 (11.3)
	Occurrence (%)	12.5 (3.5)
Knee-Hip Left	Max RPA (°)	34.3 (9.3)
	Occurrence (%)	13.7 (2.7)
Hip-Back Right	Max RPA (°)	60.1 (22.0)
	Occurrence (%)	27.1 (5.3)
Hip-Back Left	Max RPA (°)	59.8 (21.9)
	Occurrence (%)	27.0 (5.2)

Notes: Occurrence (%) = Occurrence of the maximal RPA: negative value = pre-gripping phase; 0 to 50% = lifting phase; RPA = Relative Phase Angle.

3.4. Correlations between Inter-joint Coordination and Physical Capacity

Significant negative correlations were found between all strength individual parameters and the H-B inter-joint coordination ($p < 0.05$). In other words, the strongest participants were the ones who exhibited more simultaneous extension of the back and hips, while weaker participants exhibited more sequential extension. However, no correlation was found between K-H (right or left) and all the parameters. No correlation was found between H-B (right or left) inter-joint coordination and isometric endurance of back flexors and extensors (Table 4).

Table 4.

Correlations between physical capacity indicators and inter-joint coordination.

	H-B R. max RPA	H-B L. max RPA	K-H R. max RPA	K-H L. max RPA
Leg lifting strength	**-0.805****	**-0.770****	-0.191	-0.156
Knee extension strength	**-0.705****	**-0.712****	-0.047	-0.138
Knee flexion strength	**-0.633***	**-0.628***	-0.156	-0.140
Back extension strength	**-0.593***	**-0.587***	-0.246	-0.319
Back flexion strength	**-0.596***	**-0.601***	-0.243	-0.399
Back extensors' endurance	0.369	0.360	-0.133	-0.014
Back flexors' endurance	0.382	0.318	-0.375	-0.348

Pearson correlation coefficients.
Notes: R. = Right; L. = Left; max = maximum; RPA = Relative Phase Angle.
Bold faces = $p < 0.05$; ** = $p < 0.01$ (1 tailed); * = $p < 0.05$ (1 tailed).

3.5. Evidence of Fatigue

All subjects reached a 17 ('very hard') rating on the Borg RPE scale at the end of the task. Significant changes in HR were found between the first and last bouts of the task ($p < 0.001$). Inter-personal variation in total number of lifts and the corresponding HR were observed (Fig. 19). Subjects started the task with an average HR of 79 beats/min and ended that task with a HR of 154 beats/min (Table 5).

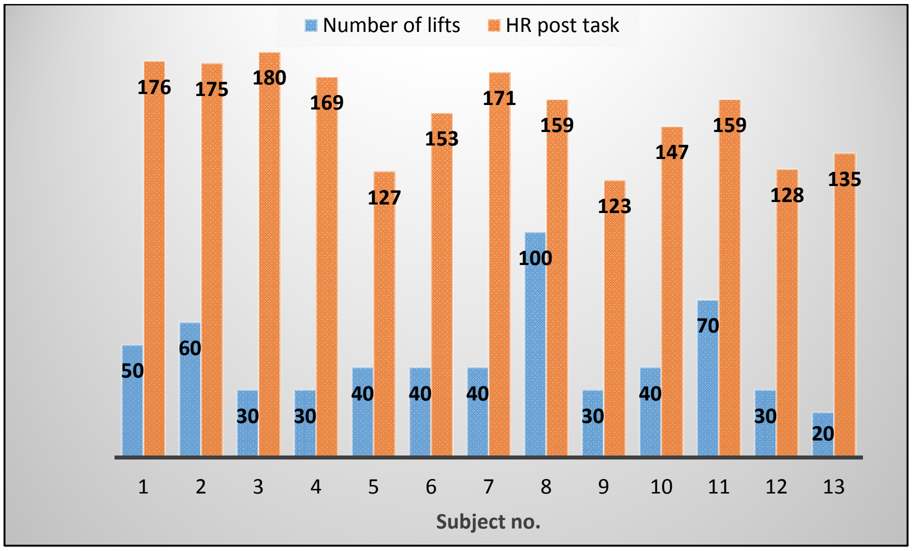


Fig. 19. Variation in post-task HR and total number of lifts among 13 subjects.

Table 5.

Mean values and standard deviation (in parentheses) for heart rate and fatigue results from the Borg RPE scale.

Variables	Pre-test M (SD)	Post-test M (SD)	*P*[1]
Borg RPE scale	6.6 (0.5)	17.1 (0.5)	**< 0.001**
HR (bpm)	78.9 (10.7)	154.0 (20.3)	**< 0.001**
Normalized HR (%)	40.3 (5.5)	78.7 (10.2)	**< 0.001**

1. Dependent T-test: Test variable (Pre-test; Post-test).
Bold faces = $p < 0.05$.

Paired t-test analysis between the MF of the EMG signals recorded during the sub-maximal isometric tests of localized muscular fatigue (EMG pre- and post-tests) showed a significant fatigue effect on right and left ES and left GM muscles MF (Fig. 20) ($p < 0.05$). However, no difference was found in the EMG value of the VL, BF and right GM muscles.

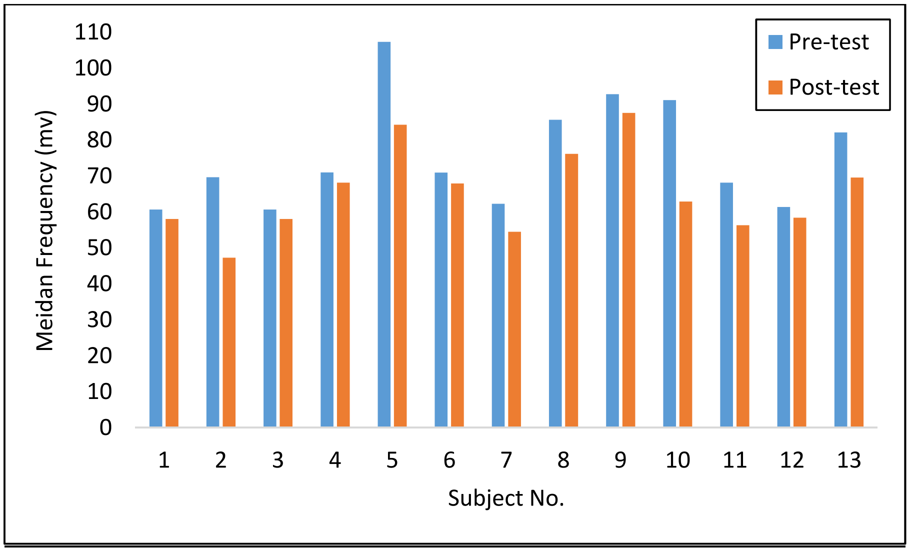


Fig. 20. Illustration of a decrease in MF between the pre and post EMG of left ES muscle.
Notes: MF = Median Frequency

Table 6 summarizes the changes in EMG fatigue variables of leg and back muscles between the EMG pre- and post-tests.

Table 6.

Mean (M) values and standard deviation (SD, in parentheses) in the EMG MF before and after fatigue for the ES, GM, BF and VL muscles.

Variables	Pre-test M (SD)	Post-test M (SD)	***P*** [1]
L. ES (Hz)	76.9 (14.8)	65.9 (12.2)	**0.001**
R. ES (Hz)	75.5 (19.2)	66.9 (20.3)	**0.048**
L. GM (Hz)	63.7 (15.6)	54.2 (10.5)	**0.016**
R. GM (Hz)	64.6 (13.8)	58.6 (12.4)	0.113
L. BF (Hz)	92.3 (21.6)	95.8 (14.6)	0.480
R. BF (Hz)	101.5 (17.9)	92.2 (19.0)	0.092
L. VL (Hz)	76.7 (10.3)	73.8 (10.3)	0.176
R. VL (Hz)	72.9 (18.6)	70.5 (18.4)	0.321

Notes: L. = Left; R. = Right;
1. Dependent T-test: Test variable (Pre-test; Post-test).
Bold faces = $p < 0.05$.

3.6. Inter-joint Coordination and Fatigue

An increase in maximal RPA was observed in K-H and H-B inter-joint coordination at the last lifting bout. This increase was observed to be higher at the H-B ($p = 0.18$) joints than the K-H ($p = 0.26$). However, neither showed significant fatigue effects. Different changes in H-B maximal RPA were observed when subjects were classified based on their lifting technique (Fig. 21).

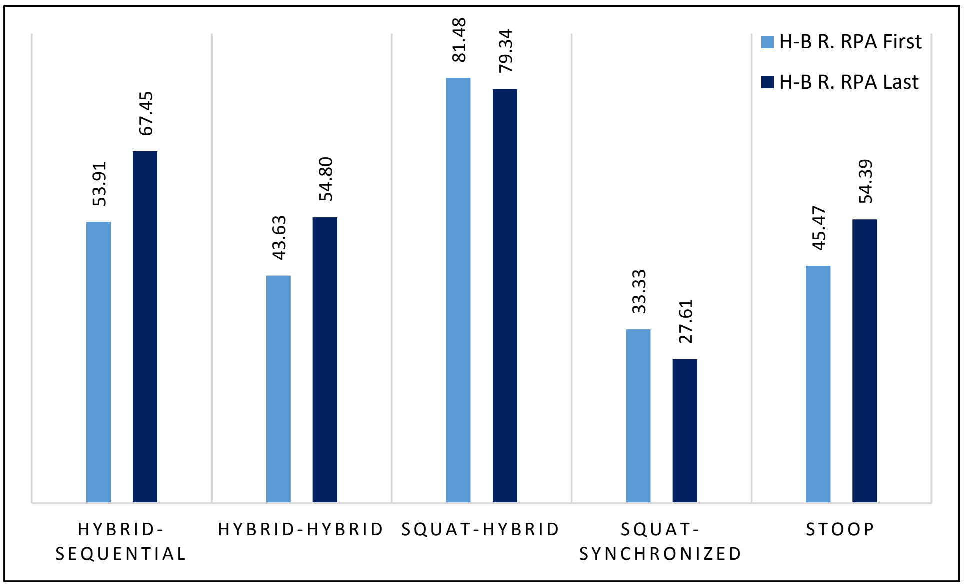


Fig. 21. Illustration of changes in H-B maximal RPA between the first and last bouts, when classified based on lifting technique exhibited by the subjects.
Notes: R. = Right; First = first bout; Last = last bout

Overall, no significant difference was found in the inter-joint coordination variables between the first and the last lifting bouts (Table 7).

Table 7.

Mean values (M) and standard deviation (SD) for the variables related to knee flexion angles, allowing to highlight the particular lifting strategy used by females.

Variables	First Bout M (SD)	Last Bout M (SD)	p^1
K-H R. max. RPA	31.3 (14.0)	34.1 (11.3)	0.259
K-H L. max. RPA	31.9 (11.2)	34.3 (9.3)	0.373
H-B R. max. RPA	51.7 (21.7)	60.1 (22.0)	0.176
H-B L. max. RPA	50.1 (22.4)	59.8 (21.9)	0.134

Notes: L. = Left; R. = Right;

1. Dependent T-test: Test variable (First bout; Last-bout).

Kinematic and kinetic variables at the peak L5/S1 moment also did not show any significant difference from the first and the last bouts (Table 8).

Table 8

Mean values (M) and standard deviation (SD) for the peak L5/S1 resultant moments and corresponding kinematic values during lifting phase of the first and last bouts.

Variables	First Bout M (SD)	Last Bout M (SD)	p^1
Peak L5/S1 resultant moment (N·m)	193.5 (28.0)	194.8 (24.1)	0.777
- Occurrence (%)	16.3 (6.7)	17.9 (7.4)	0.428
- Right knee angle (°)	46.6 (21.7)	46.4 (21.2)	0.931
- Lumbar flexion angle (°)	56.1 (14.6)	57.8 (19.2)	0.412
- Trunk inclination (°)	85.0 (13.0)	87.6 (15.7)	0.310

1. Dependent T-test: Test variable (First bout; Last-bout).
Notes: Occurrence (%) = Occurrence of resultant moment: negative value = pre-gripping phase; 0 to 50% = lifting phase.

4. Discussion

The purpose of this study was to determine the relationships between physical capacity indicators and lifting coordination in females. In addition, we sought to examine the effects of fatigue on inter-joint coordination. We had hypothesized that females with higher physical capacity indicators would display a more synchronized inter-joint coordination during lifting. We had also hypothesized that inter-joint coordination would become more sequential due to fatigue.

In the current study, we sought to determine whether inter-individual strength differences among females may influence their movement patterns during a lifting task of a 15 kg box. In addition to the challenging weight, the task was designed to induce fatigue in an attempt to disclose fatigue related differences in movement patterns. As a whole, results show significant associations between all strength test measures, but not endurance test measures, with lifting coordination. In addition, although fatigue was induced by the repetitive lifting task as evidenced by increases in heart rate and perceived task difficulty as well as decreased MF of the back extensors, none of these changes affected lifting kinematics, showing an absence of fatigue effect on lifting coordination.

4.1. Inter-joint Coordination and Physical Capacity

The strongest negative correlation found was between the isometric leg lifting strength and H-B RPA (r=-0.805). Lifting strength is a composite of hands, arms, shoulders, trunk and hip strength and there is a varying demand of the lifted load on each of these periarticular muscle groups (Kumar 2004). Knee extension strength showed the second strongest correlation with lifting coordination (r=-0.712). The importance of knee extensor strength in lifting loads from low height is well established, and it was found to be an intrinsic determinant of the adopted posture at the onset of the lift in a previous study (Li and Zhang 2009). In our study two subjects who adopted a stoop technique were also the subjects with the lowest knee extension strength (Fig. 11, subjects 9 and 10). Insufficient knee strength may have limited their ability to lift with flexed knees and can explain their tendency to use only their back strength, as suggested in previous studies (Schipplein, Trafimow et al. 1990, Li and Zhang 2009). However, knee extension strength has not been previously shown to be related to inter-joint coordination of the H-B segments, which we are the first to show here. Surprisingly, knee flexion and back flexion showed higher correlation coefficients to H-B RPA ($r=-0.633$ and $r=-0.601$ respectively) than back extension strength ($r=-0.593$). That is despite the fact that back strength has been established as one of the factors that limits lifting capacity (Zhang and Buhr 2002). However, despite these small differences in correlation coefficients, all of these aforementioned ones are significant at least at the $p < 0.05$ level.

In the most closely comparable study by Plamondon (2014), the majority of female subjects adopted a squat posture and exhibited a sequential pattern during lifting a 15 kg box. However, these females were experienced MMH handlers, and not novices such as in our experiment. The majority of subjects in our study adopted a semi-squat posture and there was interpersonal variability in terms of movement patterns which resulted in either of three lifting strategies: synchronized, sequential or hybrid. H-B inter-joint coordination and consequently its RPA is a direct contributor to this variability. This choice of lifting technique is supported by previous gender comparison studies which have concluded that females tend to utilize more movement from the hips, bend less forward and maintain the trunk straighter than males (Lindbeck and Kjellberg 2001, Davis, Splittstoesser et al. 2003, Marras, Davis et al. 2003). Also, females are on average less strong than males, however strength differences are dependent on muscle groups and can vary between 33% to 86% of male's muscle strength, which in turn can be another factor affecting variability in lifting technique and correlation between strength indicators (Chaffin, Andersson et al. 2006). Therefore, it is likely that these discovered correlations are applicable to females only.

Our work has extended the analysis of predictors of lifting technique with a higher number of strength tests, as well as the addition of a trunk flexion strength test. Most of the previous studies examined only the anterior musculature of the hips (knee extensors), and-or the posterior musculature of the trunk (back extensors) (Trafimow, Schipplein et al. 1993, Zhang and Buhr 2002, Li and Zhang 2009). Based on the results of our study, it may be suggested that hip extensors and back flexors also play an important role in affecting one's lifting technique (in this specific case, females'). In addition, it appears that the discovered correlations between isometric torso and lower limbs strength and H-B RPA affects not only the adopted posture at the onset of the lift but also an element of movement pattern related to H-B inter-joint coordination. Higher strength capabilities would therefore lead to a lower maximum RPA of H-B segments, which in turn results in a more coordinated movement between the hip and the back. On the other hand, higher RPAs might lead to a state where hip extension is almost complete and in order to complete the lift, it is only the back that carries the load until it is fully extended. This scenario may potentially put the back in a more compromised position, which would therefore increase the risk of an injury. Proactive strength training in ergonomics targeting the aforementioned muscles might be beneficial to improve lifting performance by way of leading to more synchronized lifting coordination. However, strength training would need to be accompanied by task-specific training for optimal transfer and performance based feedback in order to achieve the optimal level of coordination.

4.2. Inter-joint Coordination and Fatigue

Our results show that EMG MF was significantly affected by the repetitive nature of the task, suggesting that muscle fatigue was successfully induced (Côté et al. 2002). However we did not find any significant changes in inter-joint coordination variables, whether kinetic or kinematic. Kinematic alteration in terms of increased lumbar flexion was previously reported to occur after a fatiguing lifting task, however this study was conducted on a gender-balanced group (Dolan 1998). In addition, decreased range of motion in the knee and hip joints and an increased phase angle between the hip and the lumbar joints were previously documented at the end of a repetitive lifting test (Sparto, Parnianpour et al. 1997). However, that study was conducted on males only, and it also unknown what lifting techniques these males were adopting. Compared to these studies, we have not found any kinematic changes in lumbar flexion, knee flexion or trunk inclination at the end of the lifting task, even though other data suggests that fatigue did occur (Table 6).

An increase of a relative phase angle between hip and trunk extension has been previously reported to occur with repetitive lifting in another study (van Dieën, van der Burg et al. 1998). However in this study, the adopted lifting posture at the onset of the lift was documented. Among the ten male participants in this study, four adopted the stoop posture, five used the squat posture and only one exhibited a semi-squat posture. In addition, subjects who initially adopted a squat posture were observed to switch to more stoop oriented posture at the end of the task (van Dieën, van der Burg et al. 1998).

In our study however, among thirteen female participants, nine adopted a semi-squat posture, three adopted a squat posture and only one adopted a stoop posture. We were expecting to show an increase in RPA angles in both K-H and H-B inter-joint coordination with fatigue. Although no significant changes were discovered, we did observe an increase in K-H RPA (p=0.259) and a greater increase in H-B RPA (p=0.134). We also have not observed or measured any changes in the classification of adopted posture as a result of lifting-related fatigue. The fact that the aforementioned studies that showed coordination changes with fatigue were all conducted on males or on gender-balanced groups might suggest that females indeed respond differently to lifting-related fatigue, which could be due to various factors such as muscle fiber composition or motor control patterns (Côté, 2012). Recent studies showed gender differences in neck and shoulder muscle activation patterns during a fatigue induced repetitive pointing task (Fedorowich, Emery et al. 2013). Different fatigue mechanisms between the genders could explain these findings. In addition, the difference in lifting techniques within male and female sub-samples may further explain the observed differences between studies using gender-diverse groups of participants.

In addition to variations in lifting techniques, differences between studies in loads lifted may also explain differences in findings among studies. The reported kinetic and coordination changes in the aforementioned studies were achieved by a repetitive lifting task using a relatively light load (10% of the body weight) which allowed to lift greater numbers of repetitions. In our study, due to a challenging load – 15 kg, the number of repetitions varied as low as 20 lifts and as high as 100 lifts. In some cases the load was 30% of the subject's body weight, which led to an increase in heart rate in addition to muscular fatigue. This is also the reason why we chose to use the RPE Borg scale and not the CR10 scale, as it is capable to capture ratings of breathlessness as well as local exertion and fatigue from the working muscles involved. Our stoppage criterion was a score of 17 on the Borg RPE scale, which corresponds to very strenuous perception of exertion. For healthy subjects, HR of 170 beats/min corresponds roughly to an RPE rating of 17 (Borg 1998). In our study, 8 out of 13 subjects reached HR levels between 160-180 beats/min, while 4 subjects had HR values between 120-135 beats/min, however all subjects rated their RPE as 17 at the end of the task. This may reflect that there was some variability in the interpretation of scores of 17, with likely some participants experiencing some global whole-body fatigue, and some more localized muscle fatigue. We were very cautious in our protocol with making sure that no injury would occur to our female subjects, due to the relatively high load of 15 kg and the fatigue-inducing task. However, post factum, if we would have increased the Borg stoppage criteria from 17 to 18, perhaps we would have seen all subjects reach the relevant HR levels, increase the number of repetitions and observe more constant kinematic and movement pattern changes across the group. Taken together, these findings suggest that females should be considered separately in lifting-related fatigue studies, and more research should be done to examine the effect of fatigue on females in MMH.

4.3. Limitations

Our objectives in this study were related directly to inter-joint coordination of the K-H and H-B. Inter-joint coordination only becomes relevant when there is a moderate knee flexion. Therefore, on the one hand we were hoping to have as many female subjects as possible using a squat or semi-squat techniques in order to make our point. On the other hand, we wanted to allow the subjects as much freedom as possible to choose and use their preferred lifting technique. This is why we had to exclude two subjects from the inter-joint coordination analysis, since their chosen lifting technique was a stoop one. In general, our study has somewhat low sample size. In addition, we limited our analyses to the sagittal plane and our analysis could not have captured movements in the frontal plane. Finally, our results should be interpreted in contexts similar to the one in which the study was accomplished (relatively high load, healthy young adult novice female lifters, laboratory conditions).

5. **Conclusion**

This study showed that individual strength characteristics are one of the factors that can influence movement patterns of a lifting technique. Correlations suggest that isometric lifting capacity and strength of both the anterior and posterior musculature of the hips and the trunk may play a role in affecting the inter-joint coordination of the hip-back segments. These results are pertinent when the initial adopted posture is semi-squat or squat, meaning that a moderate knee flexion is present and this posture was indeed assumed by most females.

Acknowledgements

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CONCLUSION

The principal objective of this thesis was to explore the relationships between strength abilities of females and their inter-joint coordination patterns during a lifting task of a 15 kg box from a floor level height. Previous research has already established that gender differences are greatest when load's magnitude is the same for men and women and when the box is located on the floor. Under these specific settings, back posture and back loading are at their greater magnitude (Plamondon, Larivière et al. 2014). Surprisingly, major gender differences in lifting technique were not found in the initial adopted posture but in the movement patterns of lifting, and specifically in the knee-hip inter-joint coordination (Plamondon, Larivière et al. 2014). These findings led us to believe that perhaps strength of involved musculature during lifting would have an effect on its movement patterns among females. We therefore sought to examine this hypothesis by measuring isometric strength of females and having them to perform a challenging lifting task of a heavy 15 kg box from the floor level height.

We found a significant negative correlation between the hip-back inter-joint coordination and the following strength factors: leg lifting strength, knee extension and flexion strength and back extension and flexion strength. A stronger female will have a smaller RPA, the hip extension will lead the back extension but the delay between them will be smaller. On the other hand, less strong females will exhibit a greater distal to proximal pattern between the hip and the back, which means the hip extension will end much earlier than back extension. In this case it will leave the back in a more exposed position, as it becomes the only segment handling the imposed moments for a longer period of time. Taken together, the results of this study further emphasize the fact that defining the lifting technique by the posture assumed at the beginning of the lift has a limited meaning, and movement patterns through lift execution are considered more important factors in describing it (Scholz 1993, Burgess-Limerick, Abernethy et al. 1995, Lindbeck and Kjellberg 2001, Plamondon, Larivière et al. 2014).

Furthermore, findings of our study might have important implications on proactive training in ergonomics. They support findings of previous work, which suggest that individual strength characteristics are inherent determinants of a lifting technique (Schipplein, Trafimow et al. 1990, Puniello, McGibbon et al. 2001, Li and Zhang 2009). They can also add to an explanation of why training people to lift in a certain way has failed (Pheasant 1986, Burgess-Limerick 2003). Instead, it seems that specific strength training may be a good way to improve not only strength abilities but overall lifting coordination. Strength training programs targeted for all or parts of the aforementioned muscles, designed according to scientific strength training principles, may be prescribed as part of proactive ergonomic training. With the right guidance, gains in strength might lead to an improved performance, and resulting in a safer execution of the lift of the lift specifically for the back. This in turn could lead to safer training and performance of manual material handling for females. Having more and healthier females join the manual material handling workforce could make a significant contribution to economic growth while maintaining health and safety costs at a minimum level. However, more studies combining work-related problems with scientifically-sound solutions are necessary to optimize this kind of impact.

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APPENDICES

A. Consent Form (English version)

Effects of leg and back strength, and trunk isometric endurance on lifting coordination of females

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Consent form

Hôpital juif de réadaptation Jewish Rehabilitation Hospital

1 - Title of project

Effects of leg and back strength, and trunk isometric endurance on lifting coordination of females

2 - Researcher in charge of project

Julie Côté, Ph.D. Associate Professor, Department of Kinesiology and Physical Education, McGill University, (514) 398-4184 ext. 0539, (450) 688-9550, ext. 4813.

André Plamondon, Ph.D., Department of OHS Problem Prevention and Rehabilitation, IRSST, (514) 288-1551, ext. 279.

Michael Yehoyakim, B.Sc., Master Student in Kinesiology, McGill University, (514) 430-4607.

3 - Introduction

Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks and inconvenience as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you deem useful to the researcher and the others members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

4 - Project description and objectives

The objective of this research is to measure the relationships between leg and back strength and endurance with the lifting posture and coordination of females, during a manual material handling task. Twenty healthy adult females will be recruited to complete this study. Participants will perform two sessions: a first session of preparation and 30 minutes of strength and endurance tests, and a second session of preparation and 20 minutes of a task of lifting boxes. Equipment will be placed on participants in order to record muscle activity, body motion, external forces and heart rate. The long-term objectives of this research are to better understand the origin of gender differences in lifting performance, which can lead to the identification of safer guidelines for manual material handling in women.

5 - Nature and duration of participation

The experimental procedure will be performed at the Institute Robert-Sauvé for Research in Occupational Health and Safety (IRSST). You are asked to participate in 2 experimental sessions, the first one lasting approximately 3h and the second one lasting also approximately 3h, with at least 72 hours in between. During each session, there will be two phases: a preparation phase, and an experimental phase. We will ask you to wear sport shoes and a tight fitting tank top. None of the procedures used in this study are invasive.

In the first session, the preparation phase will last approximately 30min. Surface electrodes will be fixed on the skin over muscles of trunk and legs in order to measure muscle activity. After this preparation phase, you will be asked to complete several efforts using your trunk and leg muscles while we measure your strength and endurance. This experimental phase will last approximately 30min.

In the second session, the preparation phase will last approximately 1 hour. Surface electrodes will be fixed on the skin over muscles of your trunk and legs to measure muscle activity. Reflective markers will be placed over your trunk, arms and legs in order to track their movements with video images. You will be asked to complete several short efforts using your trunk and leg muscles. After the preparation phase, you will be asked to perform a task of lifting boxes for a total of approximately 20 minutes (Figure 1). The lifting task will consist of lifting 15 kg boxes from the floor, putting them on a shelf at waist height and lower them back. You will be asked to lift the boxes until you are fatigued. At various points during the task, the research equipment will collect data. Each 10 lifts you will be asked to stop and the researcher will ask you to give your subjective opinion about the difficulty of the task and your discomfort during the task. You are free to leave the experiment at any point if you do not wish to continue, or if you are not comfortable with the procedure.

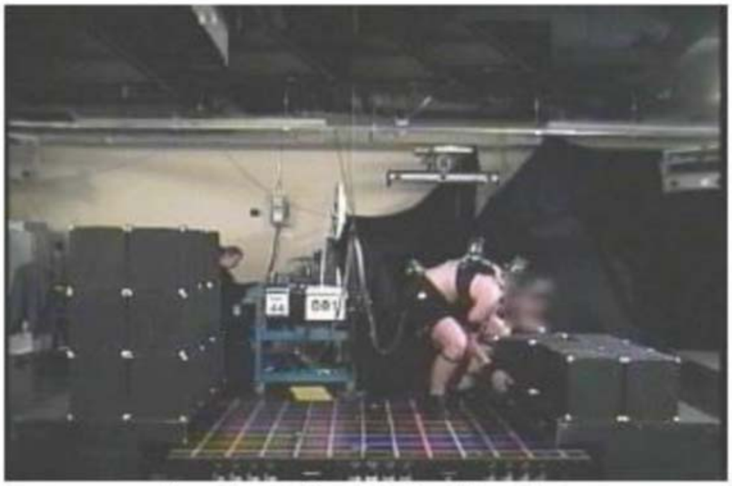

Figure 1: experimental setup, lifting a box

6 - Advantages associated with my participation

As a participant you will receive no direct benefit from your involvement in this study. However, you will contribute to the fundamental science of human physiology and biomechanics and to applied knowledge in ergonomics and occupational health.

7 - Risks associated with my participation

None of the techniques used are invasive. Your participation in this project does not put you at any medical risk.

8 - Personal inconvenience

The duration of each session (approximately 3h for the first session and 3h for the second session) and the fact that you need to come two times may represent an inconvenience for you. The possibility that a few small areas (8, 3x3 cm each) of the skin over your back, stomach, legs and arms may have to be shaved before positioning the electrodes might also be an inconvenience to you. The material used respects the usual hygiene norms. However, although it is hypo-allergenic, the adhesive tape used to fix the electrodes on your skin may occasionally produce some slight skin irritation. Should this happen, a hypo-allergic lotion will be applied on your skin to relieve skin irritation. You may experience some slight fatigue towards the end of the sessions, which may cause some leg, trunk, back muscle tenderness or stiffness. If this occurs, symptoms should dissipate within 48 hours following the completion of the protocol. A clinician will be present at all times during the protocol in case of allergic reaction, non-anticipated injury or accident.

9 - Access to my medical file

No access to your medical file is required for this study.

10 - Confidentiality

All the personal information collected for this study will be codified to insure its confidentiality. Only the people involved in the project will have access to this information. However, for means of control of the research project, your research records could be consulted by a person mandated by the REB of the CRIR establishments or by the ethics unit of the Ministry of health and social services, which adheres to a strict confidentiality policy. Information, including video images, will be kept under locking key at the research center of the Jewish Rehabilitation Hospital by the person responsible for the study for a period of five years following the end of the study, after which it will be destroyed. If the results of this research project are presented or published, nothing will allow your identification.

12 - Withdrawal of subject from study

Participation in the research project described above is completely voluntary. You have the right to withdraw from the study at any moment. If ever you withdraw from the study, all documents concerning yourself will be destroyed at your request.

13 - Responsibility

By accepting to participate in this study, you do not surrender your rights and do not free the researchers, sponsor or the institutions involved from their legal and professional obligations.

14 - Monetary compensation

No monetary compensation will be given to you for participation in this protocol. Transport costs encumbered by our participation in this research can be reimbursed upon request and upon receipt of appropriate documentation.

15 - Contact persons

If you need to ask questions about the project, signal an adverse effect and/or an incident, you can contact at any time André Plamondon at (514) 288-1551,ext. 279 or Michael Yehoyakim at michael.yehoyakim@mail.mcgill.ca or at 514-430-4607. You may also contact M. Michael Greenberg, local commissioner for complaints at the JRH, at (450) 688-9550, extension 232.

Also, if you have any questions concerning your rights regarding your participation to this research project, you can contact Ms. Anik Nolet, Research ethics co-ordinator of CRIR at (514) 527-4527 ext. 2649 or by email at anolet.crir@ssss.gouv.qc.ca.

CONSENT

I declare to have read and understood the project, the nature and the extent of the project, as well as the risks and inconveniences I am exposed to as described in the present document. I had the opportunity to ask all my questions concerning the different aspects of the study and to receive explanations to my satisfaction.

I, undersigned, voluntarily accept to participate in this study. I can withdraw at any time without any prejudice. I certify that I have received enough time to take my decision.

A signed copy of this information and consent form will be given to me.

NAME OF PARTICIPANT (print): ______________________________

SIGNATURE OF PARTICIPANT: ______________________________

SIGNED IN ____________________, on ________________, 20_____.

COMMITMENT OF RESEARCHER

I, undersigned, ______________________________, certify

(a) having explained to the signatory the terms of the present form ;

(b) having answered all questions he/she asked concerning the study ;

(c) having clearly told him/her that he/she is at any moment free to withdraw from the research project described above; and

(d) that I will give him/her a signed and dated copy of the present document.

____
Signature of person in charge of the project or representative

SIGNED IN _________________, on ________________________ 20__.

B. Consent Form (French version)

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Formulaire de consentement

Hôpital juif de réadaptation
Jewish Rehabilitation Hospital

1 - Titre du projet

Effets de la force des jambes et du dos et de l'endurance isométrique sur la coordination du soulevé de charges chez les femmes

2 - Responsable(s) du projet

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André Plamondon, Ph.D., Chercheur, Département de prévention des problématiques de SST et réadaptation, Institut de recherché Robert-Sauvé en santé et en sécurité du travail (IRSST), (514) 288-1551, poste 279.

Michael Yehoyakim, B.Sc., étudiant à la maîtrise en kinésiologie, université McGill, (514) 430-4607.

3 - Préambule

Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel affecté au projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

4 - Description du projet et de ses objectifs

L'objectif de cette recherche est de mesurer les relations entre la force et l'endurance des jambes et du dos avec la posture et la coordination des femmes durant une tâche de manutention. Vingt femmes seront recrutées pour participer à cette étude. Les participants effectueront deux séances : une première séance de préparation et de 30 minutes de tests de force et d'endurance, et une deuxième séance de préparation et de 20 minutes d'une tâche de soulevé de boites. L'équipement sera fixé sur les participants afin de mesurer l'activité des muscles, les mouvements corporels, les forces externes et la fréquence cardiaque. Les objectifs à long terme de cette recherche sont de mieux comprendre l'origine des différences de performance en manutention entre les hommes et les femmes, ce qui pourrait mener à l'identification de normes de travail plus sécuritaires chez les femmes.

5 - Nature et durée de la participation

Le protocole de recherche sera effectué à l'Institut de recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST). On vous demande de participer à deux séances expérimentales, la première d'une durée approximative de 3h et la deuxième d'une durée approximative de 3h, avec au moins 72h entre les deux séances. Durant chaque séance, il y aura deux phases : une phase de préparation et une phase expérimentale. On vous demandera de porter des souliers de sport et une camisole ajustée à la peau. Aucune des procédures utilisées dans cette étude n'est invasive.

Durant la première séance, la phase de préparation durera environ 30min. Des électrodes de surface seront fixées sur la peau de votre colonne et de vos jambes afin de mesurer l'activité des muscles. Après cette phase de préparation, on vous demandera d'effectuer plusieurs efforts avec les muscles de votre colonne et de vos jambes pendant qu'on mesurera votre force et votre endurance. Cette phase expérimentale durera environ 30min.

Durant la deuxième séance, la phase de préparation durera environ 1h. Des électrodes de surface seront fixées sur la peau de votre colonne et de vos jambes afin de mesurer l'activité des muscles. Des marqueurs réfléchissants seront fixés sur la peau de votre colonne, de vos bras et de vos jambes afin de mesurer leurs déplacements à l'aide d'images vidéo. On vous demandera d'effectuer quelques efforts de courte durée avec votre colonne et vos jambes. Après cette phase de préparation, on vous demandera d'effectuer une tâche de soulevé de boites pour une durée totale d'environ 20min (Figure 1). La tâche de soulevé consistera en soulever des boites de 15kg à partir du sol, les placer sur une étagère à la hauteur de la taille, et de les redescendre. On vous demandera de soulever les boites jusqu'à ce que vous soyez fatiguée. À certains moments durant la tâche, on enregistrera des données. Après chaque 10 soulevés on vous demandera d'arrêter et le chercheur vous demandera de donner votre évaluation subjective de la difficulté de la tâche et de l'inconfort relié à la tâche. Vous serez libre d'abandonner le protocole à tout moment si vous ne voulez pas continuer ou si vous êtes inconfortable à propos de la procédure.

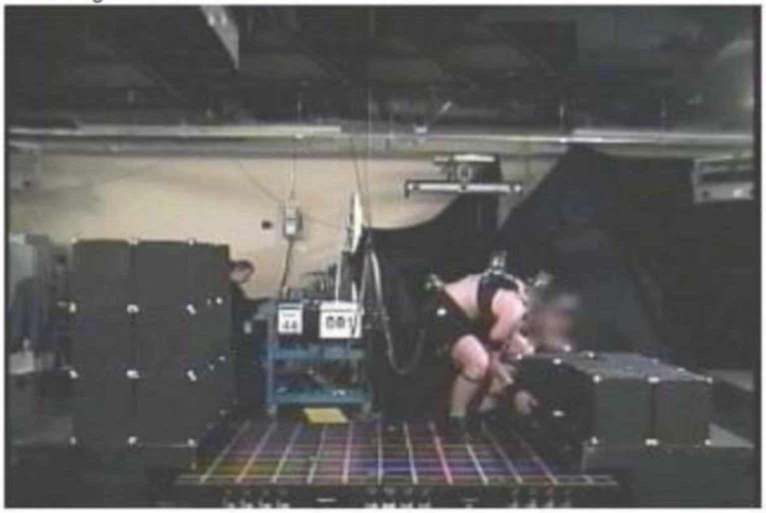

Figure 1 : montage expérimental. Soulevé de boite.

6 - Avantages pouvant découler de votre participation

En tant que participant, vous ne retirerez personnellement pas d'avantages à participer à cette étude. Toutefois, vous aurez contribué à l'avancement de la science fondamentale de la physiologie humaine et de la biomécanique et aux connaissances appliquées de l'ergonomie et la santé au travail.

7 - Risques pouvant découler de votre participation

Aucune des procédures décrites n'est invasive. Votre participation à cette recherche ne vous fait courir aucun risque médical.

8 - Inconvénients personnels

La durée de la séance expérimentale (environ 3h pour la première séance et 3h pour la deuxième séance) et le fait de devoir venir deux fois peut représenter un inconvénient pour certaines personnes. La possibilité que quelques régions (8, 3x3 cm chaque) de la peau de votre dos, de vos jambes et de vos bras doivent être rasées avant d'y apposer des électrodes peut également représenter un inconvénient pour vous. Le matériel utilisé respecte les règles d'hygiène usuelles. Toutefois, bien qu'il soit hypo-allergène, le ruban adhésif utilisé pour maintenir les électrodes sur la peau peut occasionnellement provoquer de légères irritations de la peau. Le cas échéant, une lotion hypo-allergène sera appliquée pour soulager l'irritation cutanée. De plus, il est possible que vous ressentiez un peu de fatigue vers la fin de la séance expérimentale, ce qui pourrait causer de la sensibilité ou de la raideur des muscles des jambes, de la colonne et du dos. S'ils se manifestent, les symptômes devraient disparaître dans les 48 heures suivant la fin du protocole expérimental. Un clinicien sera présent en tout temps durant le protocole en cas de réaction allergique, blessure ou accident non anticipés.

9 - Accès à mon dossier médical

L'accès à votre dossier médical n'est pas requis pour cette étude.

10 - Confidentialité

Tous les renseignements personnels recueillis à votre sujet au cours de l'étude seront codifiés afin d'assurer leur confidentialité. Seuls les membres de l'équipe de recherche y auront accès. Cependant, à des fins de contrôle du projet de recherche, votre dossier de recherche pourrait être consulté par une personne mandatée par le CÉR des établissements du CRIR ou de l'Unité de l'éthique du ministère de la Santé et des Services sociaux, qui adhère à une politique de stricte confidentialité. Les données, incluant les images vidéo, seront conservées sous clé au centre de recherche de l'Hôpital juif de réadaptation par le responsable de l'étude pour une période de 5 ans suivant la fin du projet, après quoi, elles seront détruites. En cas de présentation de résultats de cette recherche ou de publication, rien ne pourra permettre de vous identifier.

12 - Retrait de la participation du sujet

Votre participation au projet de recherche décrit ci-dessus est tout à fait libre et volontaire. Il est entendu que vous pourrez, à tout moment, mettre un terme à votre participation. En cas de retrait de votre part, les documents électroniques et écrits vous concernant seront détruits à votre demande.

13 - Clause de responsabilité

En acceptant de participer à cette étude, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs, le commanditaire ou les institutions impliquées de leurs obligations légales et professionnelles.

14 - Indemnité compensatoire

Aucune compensation financière ne vous sera offerte pour votre participation à cette étude. Des frais de déplacement encourus par la participation à cette recherche pourront vous être remboursés à votre demande et sur présentation de pièces justificatives.

15 - Personnes ressources

Si vous désirez poser des questions sur le projet ou signaler des effets secondaires, vous pouvez rejoindre en tout temps André Plamondon au (514) 288-1551, poste 279 ou Michael Yehoyakim à michael.yehoyakim@mail.mcgill.ca ou au 514-430-4607. Vous pouvez également contacter Monsieur Michael Greenberg, commissaire local aux plaintes de l'HJR, au (450) 688-9550 poste 232.

De plus, si vous avez des questions sur vos droits et recours ou sur votre participation à ce projet de recherche, vous pouvez communiquer avec Me Anik Nolet, coordonnatrice à l'éthique de la recherche des établissements du CRIR au (514) 527-4527 poste 2649 ou par courriel à l'adresse suivante: anolet.crir@ssss.gouv.qc.ca

CONSENTEMENT

Je déclare avoir lu et compris le présent projet, la nature et l'ampleur de ma participation, ainsi que les risques auxquels je m'expose tels que présentés dans le présent formulaire. J'ai eu l'occasion de poser toutes les questions concernant les différents aspects de l'étude et de recevoir des réponses à ma satisfaction.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux me retirer en tout temps sans préjudice d'aucune sorte. Je certifie qu'on m'a laissé le temps voulu pour prendre ma décision.

Une copie signée de ce formulaire d'information et de consentement doit m'être remise.

NOM DU PARTICIPANT : ______________________________

SIGNATURE : ______________________________

Signé à ______________________, le __________, 20_____.

ENGAGEMENT DU CHERCHEUR

Je, soussigné (e), ________________________________ , certifie

(a) avoir expliqué au signataire les termes du présent formulaire;

(b) avoir répondu aux questions qu'il m'a posées à cet égard;

(c) lui avoir clairement indiqué qu'il reste, à tout moment, libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus;

et (d) que je lui remettrai une copie signée et datée du présent formulaire.

____
Signature du responsable du projet
ou de son représentant

Signé à _________________, le _____________ 20__.