Difference between male and female workers lifting the same relative load when palletizing boxes

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Abstract

A few biomechanical studies have contrasted the work techniques of female and male workers during manual material handling (MMH). A recent study showed that female workers differed from males mostly in the strategy they used to lift 15-kg boxes from the ground, especially regarding task duration, knee and back postures and interjoint coordination. However, the lifting technique difference observed in females compared to males was perhaps due to a strength differences. The objective of this study was to test whether female workers would repeat the same lifting technique with a load adjusted to their overall strength (females: 10 kg; males: 15 kg), which can be considered a "relative load" since the overall back strength of females is 2/3 that of males. The task for the participants consisted in transferring boxes from one pallet to another. A dynamic 3D linked segment model was used to estimate the net moments at L5/S1, and different kinematic variables were considered. The results showed that the biomechanics of the lifting techniques used by males and females were similar in terms of task duration and cumulative loading, but different in terms of interjoint coordination pattern. The sequential interjoint coordination pattern previously seen in females with an absolute load (15 kg) was still present with the relative load, suggesting the influence of factors more intrinsically linked to sex. Considering that the female coordination pattern likely stretched posterior passive tissues when lifting boxes from the ground, potentially leading to higher risk of injury, the reason for this sex effect must be identified so that preventive interventions can be proposed.

1. Introduction

The risks of occupational back injury are still very high today. In Québec, Canada, 333,000 workers—almost 10% of the work force—experience back musculoskeletal disorders (MSDs) that interfere with their activities (EQCOTESST; Stock et al., 2011). According to this survey, back MSDs are significantly more prevalent in women (11.3%) than in men (7.6%). Risk factors are different for women because men and women with the same job titles perform different tasks (Stock et al., 2011; Lewis & Mathiassen, 2013; Messing et al.,2009; Gardner et al.,1999). In addition, even with equal physical work demands, average women are working closer to their physiological limit than men (Stock et al., 2011; Côté, 2012). Manual material handling (MMH) tasks have been associated with low back injuries in a large number of studies (Hoogendoorn et al., 1999; Kuiper et al., 1999; Lotters et al., 2003; National Research Council, 2001; da Costa et al., 2010; Nelson and Hugues, 2009). Traditionally, MMH is largely performed by men, and this has certainly contributed to the limited presence of women in MMH studies. It is not known if the findings of studies with male subjects can be extrapolated to females, considering they are smaller in size and less strong than males (Lindbeck and Kjellberg, 2001).

The literature on MMH is confusing with regard to sex differences because some studies used **A**bsolute **L**oads (**AL)** in kg and others used **R**elative **L**oads (**RL)** adjusted to strength. The former approach has better external validity with regard to the work context (same AL for males and females) while the latter has better internal validity with regard to the control of strength as an important confounding variable. Studies with AL have shown that females adopted a lifting style that made more use of their hips, whereas much of the lifting motion for males was from the lumbar spine (Marras et al., 2003). Davis et al.

(2003) found that for lifting close to the floor, the hips of females dominated and the lifting style resembled more of a squat lift than a stoop lift. In the Li and Zhang (2009) study, males were more likely to use the back-preferred strategy at the onset of a lift, whereas females more often used the leg-preferred strategy.

To control for the strength difference between sexes, some studies in MMH choose to adjust the load based on either the population capacity or the true individual capacity. For instance, Lindbeck and Kjellberg (2001) adjusted the load to 8.7 kg for females (68% of male load) and 12.8 kg for males. They found that hip-knee coordination was more in phase (synchronized) in females during a squat lift, the hip extension lagging more behind knee extension in males. This was interesting, as females are generally weaker than males, and papers investigating hip-knee coordination have found that as the load weight increases, lumbar spine motion lags further behind the lower extremity joint motion (Davis et al.,1965; Scholtz, 1993a, 1993b; Scholz et al., 1995; Burgess-Limerick et al., 1995). Three studies adjusted the weight of the load to the subjects' true individual lifting capacity (Albert et al. (2008) = 20% relative load; Sadler et al. (2011) = 0% and 10% of maximum isometric back strength (MISB); Sheppard et al., (2016) = 10%, 20% and 30% MISB), and their results concluded that there were no significant sex effects in the lifting technique (kinematics of lifting). Sheppard et al. (2016) then suggested that the findings of one sex might be used as an accurate representation of lifting technique for the other sex once actual load factors are taken into account. This may be premature, as a sex difference in interjoint coordination during lifting has been shown by Plamondon et al. (2014b), and the work of Sheppard et al. (2016) did not study this variable.

Our group initiated two studies on repetitive palletizing tasks using the same experimental design, the first with males and the second with females, in the aim of investigating the effects of expertise and sex on lifting technique. A first paper was published in 2014 (Plamondon et al., 2014a) about the lifting techniques of expert and novice male workers. It was found that expert males differed from novice males mostly in posture-related variables when transferring 15-kg boxes. A second paper was published later the same year (Plamondon et al., 2014b) where the lifting techniques of experienced female workers were compared with those of expert and novice males. It was shown that females, when lifting the same AL (15 kg) as males, had (1) a lower peak resultant moment than males during lifting, but once normalized to body size the difference disappeared; and (2) a posture very similar to that of the novice males at the peak resultant moment. Moreover, Plamondon et al. (2014b) indicated that female workers showed a sequential motion in their interjoint coordination pattern initiated by the knees, followed by the back, while expert males showed a more synchronized motion. This strategy, seen in females when lifting boxes from the ground, would likely stretch the lumbar spine passive tissues when the lumbar spine is close to its maximal flexion. This puts the handlers at greater risk of back injuries.

A question that was not discussed in our previous paper (Plamondon et al., 2014b) was whether females lifting the same RL as males would have the same lifting technique. This would help determine whether the difference in lifting technique between sexes is linked to a difference in load or other factors. To answer our question, we used the data from the second part of our research with females (which was not presented in Plamondon et al., 2014b) where they had to transfer the same RL as males (males 15-kg boxes and females

10-kg boxes). This RL was based on the assumption that women's overall lifting strength is 2/3 that of men (Mital et al.,1997). It was hypothesized that the biomechanics of the lifting technique used by female workers would be equivalent to those of males when the RL is similar, as shown by measures of joint motions and interjoint coordination.

2. Methods

The results presented in Plamondon et al. (2014b) concerned only a comparison between males and females lifting the same AL (15-kg boxes), which was the first part of our study. This paper addresses the second part of the results, where females had to lift 10-kg boxes, considered to be the same relative load as for the males (males 15-kg boxes and females 10-kg boxes). The design of this study on female handlers is the same as the one previously published (same subjects, same protocol) with the exception that the women, after handling the 15-kg boxes (see Plamondon et al., 2014b) had to repeat the tasks with 10-kg boxes (Figure 1). The tasks (depalletizing/ palletizing) were challenging in that the workers had to lift boxes from different heights, across a horizontal distance and at different paces (bringing fatigue into play), to force them to show their techniques and to see whether the groups were similar in terms of transfer time, posture and back loading. As the detailed methodology has been presented elsewhere (Plamondon et al., 2014a, 2014b), this section contains only the essentials for understanding the data analyzed.

2.1. Subjects

Three groups of subjects - the same subjects as in Plamondon et al. (2014b) - participated in the study[1]. The first consisted of 15 male experts with 15 years of experience on average (SD=9.3) and a low lifetime incidence of injuries (particularly to the back). The

[1] For details on the anthropometric data, see Plamondon et al. (2014b).

second consisted of 15 male novices with 0.5 years of experience (SD=0.4). The third group was 15 females with 7 years of experience (SD=2.3), but due to the difficulty of recruitment, the criterion of a low lifetime incidence of back injury had to be dropped. Nevertheless, each subject had to be exempt of injury in the year preceding the study. All participants completed the informed consent forms approved by the Ethics Committee of the University of Sherbrooke (Faculty of Medicine and Health Science).

The strength of each subject was evaluated in a separate experimental session. Several tests were performed, and Figure 2 presents the results of two of them: the isometric leg lifting strength test (Chaffin et al., 1978) and the isometric back extension strength test (Larivière et al., 2001). The average strength of the females was significantly lower than that of the males (Plamondon et al., 2014b) and corresponded on average to 48% – 61% of the males' strength.

2.2 Task description

At the beginning of the experiment, the participants were instructed about the importance of reproducing the technique they normally used in their work. No lifting technique was ever prescribed to the participants and no comments were given about the technique they used. A schematic description of the experiment design is available in Figure 1. The MMH task consisted **<u>for the males</u>** in transferring 24 15-kg boxes from one pallet (depalletizing) to another (palletizing), and back, five times over a 30-minute period (total box transfers: 240). The five-trip sequence was divided into two parts: the first consisted of two round trips for all 24 boxes on the pallet (total of 96 boxes handled), performed at a pace the subject would use in an eight-hour day for this type of manual handling (**self-paced**). The second part (**imposed pace**) consisted of three round trips for all 24 boxes (total of 144 boxes) at nine boxes per minute to challenge and potentially fatigue the subject. **The females** had to do the same first two round trips at the self-paced rhythm (96 boxes) but only one round trip at the imposed pace (48 boxes as opposed to the males' 144). We elected to reduce the difficulty of the task for safety reasons with regard to fatigue and the associated increased risk of injury. Just after the completion of the three round trips, the females had 30 minutes of rest, followed by two round trips with 10-kg boxes: one at a self-paced rhythm (48 boxes) and one at the imposed pace (48 boxes). As the task was not exactly the same as the men's, which could be a potential problem, fatigue tests were included in the protocol to ensure that the fatigue level was comparable. The subject's perception of general physical fatigue and back muscle fatigue was assessed with a CR-10 Borg's scale (Borg, 1982). In addition, localized muscular fatigue was evaluated during the experiment—at the beginning and after each pace condition (Figure 1)—with a standardized isometric sub-maximal task using surface electromyography (EMG). The description of this test with the results has been included in Appendix A (Supplemental Data).

The height of each pallet was 16 cm and the box dimensions were 26 cm deep by 35 cm wide by 32 cm high. The subjects were instructed to remain on the force platform and to pile the boxes (total of 24) in a column stacking pattern 4 layers high (1^{st} layer = 16 cm above the floor, 2^{nd} = 48 cm, 3^{rd} = 80 cm; 4^{th} = 112 cm) by 6 boxes/layer (3 in the front row, 3 in the back row).

2.3. Measuring systems

Stereophotogrammetric measuring systems, video cameras and an in-house force platform were used to collect the kinematic and kinetic data needed to use a dynamic 3D linked-segment model for estimating the net moments at L5/S1 (Plamondon et al., 1996). Fatigue was estimated by means of EMG (localized back muscle fatigue), heart rate and Borg's scale (perception of local and overall fatigue).

2.4. Data collection

The participants were instrumented for use of a dynamic 3D linked-segment model to estimate the net moments at L5/S1 expressed in the coordinate system of the pelvis (flexion-extension, lateral bending and torsion moments). Considering the large number of data, it was decided to analyze only the last round trip (24 boxes) of each pace condition (self-paced and imposed pace) with the 15-kg or 10-kg boxes. As there are two directions in a round trip, a going and a return, only the results in the going direction are presented here. The going direction was broken down into two different phases: a lifting phase (depalletizing) and a deposit phase (palletizing). The lifting phase includes a pre-lift (gripping), where the box is brought close to the subject without being lifted, and a take-off (lifting of the box); it ends at the midpoint of the flight period. The deposit phase begins after the lifting phase and continues until the box is deposited at its final destination on the pallet. The flight period (the period of time during which the weight of the box is completely supported by the subject's hands) was divided into two equal sections (time/2), such that the first section became an integral part of the lift phase and the second an integral part of the deposit phase.

2.5 Description of the dependent variables

Four categories of dependent variables were considered:

Temporal variables: Task duration and pace.

Fatigue variables: The subject′s level of fatigue was evaluated after each pace condition by means of: 1) EMG parameters, which include the Root Mean Square (RMS) and Median Frequency (MF) values of the right and left *longissimus* muscles; 2) Borg's assessment of perceived General fatigue ($\boldsymbol{\psi_G}$) and Back muscle fatigue ($\boldsymbol{\psi_B}$); 3) and mean heart rate (HR).

Biomechanical variables: For both the lifting and deposit phases, peak resultant moment (PRM) at L5/S1 was calculated. At PRM the following were determined: lumbar flexion angle, trunk inclination, right and left knee flexion angles and horizontal distance of the hands from the L5/S1 joints (hands-L5/S1 distance). In addition, the cumulative moment at L5/S1 was estimated as the sum of the resultant moment during flight time. To normalize the anthropometric difference between males and females, the HAT (head + arms + trunk) weight moment from L5/S1 was used. The resultant moment and the cumulative moment were divided (normalized) by the HAT moment of the subject. In addition, the horizontal distance of the hands from the L5/S1 joints was divided by the height of the subject.

Interjoint coordination variables: Interjoint coordination, as assessed using continuous relative phase angle (**RPA**) analyses (Burgess-Limerick et al., 1993, 1995; Albert et al., 2008), was studied during the lifting phase of the last round trip of each pace condition, from the floor level of the pallet exclusively (n = 24 lifts/participant). Relative phase variables were estimated between knee and hip (K-H; right and left), and between hip (right and left) and trunk (H-T). The method used was the one described in Burgess-Limerick et al. (1993). Only the rotation in the sagittal plane (flexion-extension) was considered here, and the specific phase analyzed extends from -10% to 30% of the lifting phase. The 30% threshold was used because the subject generally completed the lifting of the box at that time and was about to start turning towards the destination pallet. 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. Maximum values of relative phase between joints were calculated.

2.5 Statistical analysis

2.5.1 Statistics on biomechanical variables

Two categories of comparisons were studied: (1) the load effect among females (♀**L**: 10 vs 15 kg) and (2) the sex effect with the same RL (females: 10 kg; males: 15 kg).

(1) The load effect (10 vs 15 kg boxes) was evaluated only for females. A repeated measures ANOVA (2×4×2) was applied: Within-subjects (females); 10 kg vs. 15 kg loads; box vertical height (H) and pace (P), but only the main effect of load is presented in this comparison to simplify the description of the results.

(2) The sex effect was evaluated between males (15-kg boxes) and females (10-kg boxes). A mixed factorial ANOVA (3×4×2×2) was used: Between-subjects, three groups (G): Experts (E), Novices (N) and Females (F); Within-subjects: Vertical height (H): 16, 48, 80 and 112 cm; Horizontal distance (D): close vs. far; pace (P): self-paced vs. imposed pace. However, this model is not complete as the men did not handle the 10-kg load. The load

effect (10 kg vs 15 kg) was thus integrated into the group effect (Experts, Novices, Females). The lifting phase (G, $H_{lifting}$, $D_{lifting}$ and P) and the deposit phase (G, $H_{deposit}$, $D_{deposit}$ and P) were analyzed independently. As the task duration, flight time and cumulative loading cover both phases, the vertical height (H) and horizontal distance (D) levels considered were, exceptionally, those of the lifting phase.

As this study aimed to investigate whether a challenging MMH task would make female workers differ from their male counterparts (both expert and novice), the main interest of this paper is in the group effect (G) and the two-way interactions involving group (G×H; G×D; G×P). Therefore it was decided to present only the data relating to these differences; 3- and 4-way interactions were excluded from the analysis due to the complexity of the corresponding interpretations.

2.5.2 Statistics on fatigue and temporal variables

The same two comparisons as above were applied to the fatigue variables (Borg's assessment and heart rate) and temporal variables (duration and pace). The load effect among females (♀**L**: 10 kg vs. 15 kg) was assessed with one-way (10 kg vs. 15 kg), repeated ANOVA. The sex effect was evaluated with two-way mixed factorial ANOVA (3,2): Between-subjects, three groups (G): Experts (E), Novices (N) and Females (F); Within-subjects: pace (P): self-paced vs. imposed pace. Note that statistics for the EMG parameters are presented in Appendix A (Supplemental Data).

2.5.3 Statistics on interjoint coordination variables

One-way, repeated ANOVAs were applied to measure the sex effect on the maximum

RPAs. Left and right sides were calculated separately for each knee and hip. Only the 24 liftings from the bottom of the pallet were considered for each participant, and it must be noted that novice males were not included, their coordination being more variable than the other groups (Plamondon et al., 2014b). Furthermore, RPA curves (24) of each subject were classified with cluster analyses to identify similar and dissimilar patterns, using the medoid partitioning algorithm (NCSS software). The first step was to find the most representative medoid (method: Spath, Objective Function: Mean Distance). To do so, the 24 patterns of each subject were partitioned into two clusters, and the medoid that characterized most of the patterns was chosen as the worker's most representative pattern. Then, all the representative medoids were used to classify the subjects into one of the three possible clusters chosen (experts 15 kg, females 15 kg, females 10 kg).

2.5.4 Statistical data processing

NCSS software (version: 07.1.14; NCSS, Kaysville, UT, USA) was used to process the statistical data. For purposes of parametric analysis, the data were transformed based on the fundamental law of probabilities (van Albada and Robinson, 2007), allowing normal distributions to be obtained according to the Wilk-Shapiro test. Also, to offset a violation of sphericity in the mixed-model measurement ANOVAs, the probability threshold was adjusted using the Geisser greenhouse epsilon correction factor. For all statistical tests, a significance level of $p < 0.05$ was used. Tukey-Kramer multiple pairwise comparisons were performed in the case of significant main effects.

3. Results

The results are presented in three parts: (1) the effect of fatigue; (2) the load effect among females (♀**L:** 10 vs 15 kg); (3) the sex effect with the same RL (females: 10 kg; males: 15 kg). Note that the mean (M) and the standard deviation (SD) in the Tables integrate the conditions of vertical height, horizontal distance or pace. When results for both knees are similar, only those of the right knee are presented. The data for the males with the 15-kg boxes have been published in a previous paper (Plamondon et al., 2014b) and will not be repeated here. Hereafter, the term ″males″ refers to both experts and novices unless specified.

3.1 Control of general and localized muscle fatigue as a potential confounding variable

Was fatigue comparable in females between the 10- and 15-kg loads? The perception of general fatigue (ψ_G) and HR were significantly lower with the 10-kg boxes than with the 15-kg boxes, whereas back muscle fatigue was similar according to perception (ψ_B) (Table 1A) and as concluded from the EMG-based test of muscle fatigue (Appendix A). Overall, the different measures of fatigue suggest that the 15-kg task was psychophysically and physiologically more demanding, but without generating more localized back muscle fatigue.

Was fatigue comparable between sexes when handling the same RL? The perception of back fatigue (ψ_B) was found to be similar between males and females but not general fatigue (ψ_G), which was lower for females (Table 1B). The significant Group × Pace interaction is explained by the fact that females had approximately the same results in both paced conditions for the perception of general fatigue (ψ_G), back fatigue (ψ_B) and heart rate; this was not the case for males, where the values for the imposed pace conditions increased at a faster rate. With regard to the EMG-based test (Appendix A) and the different measures of fatigue, these suggest that physical fatigue was slightly lower for females in comparison to males during RL.

3.2 Load effect: Comparison within females: *10-kg boxes vs 15-kg boxes (*♀**L**)

The total duration of the task was significantly shorter with the 10-kg load than the 15-kg load, and this is consistent with a faster lifting pace with the 10-kg load (Table 1A). Expectedly, reducing the load from 15 kg to 10 kg decreased the L5/S1 peak resultant moment by about 15 Nm during the lifting and deposit phases (Table 2A). Reducing the load had very little impact on upper body posture (Table 2A and Figure 3) because lumbar flexion changed only slightly (lifting phase) and trunk inclination did not change at all. However, knee bending showed a significant decrease (about 5° more extended) except when the 10-kg boxes were lifted from the bottom of the pallet (Table 2A, Figure 4). Also, hands-L5/S1 distance increased by about 2 cm in the lifting phase and 4 cm in the deposit phase (Table 2A). Cumulative moment decreased by 37 Nms, or close to 25%. Normalization did not change these findings (Table 3A).

Decreasing the load had a small but significant impact on knee-hip and hip-back joint coordination in the women. Table 4 shows that the maximum right knee flexion at the initiation of the lift was 14° less with the 10-kg load than with the 15-kg load. At the PRM, the knee angles were approximately the same (48°) with both loads, which means that with the 10-kg boxes, the right knee extended 13° less than with the 15 kg-boxes. The consequence of this is that the maximum amplitude of the phase angle of the knee/hip joint was significantly less with the 10-kg boxes in comparison with the 15-kg boxes (Table 5). The same result was found with the hip/back joint coordination.

3.3 Comparison between males and females when lifting the same RL (males: 15 kg; females: 10 kg).

Task duration became similar for females and males, having approximately the same time (Table 1B). Females with the 10-kg box benefited from reduced loading on the back compared to the males (resultant and cumulative moments; Tables 2B). However, with the normalization, females had lower loading only compared to the novices (Table 3B). Posture (back and knee) changed only slightly, and the females' posture generally remained similar to that of the novice males but different from that of the experts (Table 2B). Hands-L5/S1 distance increased for the females, but they stayed closer to the box than the novices (Table 2B); normalization of this distance eliminated the differences between the males and the females (Table 3B).

The maximum phase angle amplitude of the knee/hip and hip/back joints was always higher in females than in the expert group (Table 5). In other words, females showed a more sequential pattern in their interjoint coordination than experts, even with the same RL. The cluster analysis showed that when the number of clusters is set to three (Table 6), the expert males are generally part of a distinct cluster (♂15) and the females are distributed on two different clusters (Mixed♀ and All Mixed). This result means that the females did not change their coordination pattern very much between loads of 15 kg and 10 kg.

4. Discussion

It was hypothesized that the biomechanics of the lifting technique of female workers would be equivalent to that of males when RL is similar (males 15-kg boxes and females 10-kg boxes). This hypothesis proved true for some variables such as task duration and cumulative moment, partially true for variables defining posture, and false for joint coordination pattern. However, before further discussing these findings, the potential confounding effect of fatigue must be discussed.

4.1 Fatigue

The different measures of general and localized muscle fatigue showed that fatigue differed at times between loads and sexes, depending on the measure. Fatigue was difficult, if not impossible, to control in the present study where the subjects performed self-paced transfers before imposed-pace ones, where males and females lifted more or less the same RL and where the lifting technique was not controlled, allowing load-sharing between different muscle groups. These experimental conditions were designed to increase the external validity of the study, but at the expense of internal validity. Fortunately, for safety reasons (control of fatigue), we elected to reduce the number of round trips among females, which likely helped reduce fatigue in females, making sex comparisons more valid. Another element that also played in our favor is that at a given RL, the progression of back muscle fatigue is slower in females during intermittent contractions such as the ones performed in MMH (Larivière et al., 2006). All in all, we conclude that fatigue was likely not a major confounding factor in our findings.

4.2 Lifting technique

The following paragraphs will examine if the biomechanics of the lifting technique in females, comparatively to males, are associated mainly with a change of load mass or other factors. Table 7 summarizes the main results of this study (same RLs between sexes) and the one of Plamondon et al. (2014b) (same ALs) and identifies where the effect of loads appear to be the most important factor. Two other variables are suggested when the load is not the main factor: sex and expertise. Sex has often been considered as having a role in the lifting technique (Li and Zhang, 2009; Marras et al., 2003; Plamondon et al., 2014b). Expertise (i.e. years of experience + rate of injuries) has been shown to be an important factor in the lifting technique of expert workers (Plamondon et al., 2010; 2014a). As our participants had different level of expertise, this factor was considered concomitantly to examine if it could interact with the other two.

Temporal variables (task duration, lifting pace) appear to be influenced mostly by change of load, as this effect was present in ♀**L** and in AL. Moment variables (peak and cumulative) were obviously influenced by load, but also by sex (differences in ♀L, RL and AL) because females had systematically lower moments than males due to their different anthropometries. With normalization, the sex effect nearly disappears and load effect remains a major factor particularly in the cumulative loading. This is not surprising because a change of load mass has a direct impact on the moment components (Schiepplein et al., 1990; Davis and Marras, 2000). Expertise appears to play a minor role when females are different to either experts or novices, as in the normalized peak resultant moment in RL and AL.

Posture is not so dependent on a change in load as on the moments seen in lumbar flexion and trunk inclination (Table 7 in ♀**L**). Sex effect is difficult to evaluate here, but females with seven years of experience in average do not move in the same direction as experts, being closer in posture to the novices. Body stature may also play a role in the posture adopted by males and females during lifting. Sheppard et al. (2016) found no effect of sex and load in the lumbar kinematic during lifting. Moreover, Davis and Marras (2000) did not find significant differences in the trunk position variables when load weight was reduced among males, but Faber et al. (2007) observed more trunk inclination with lighter loads (building blocks). Nonetheless, posture depends on expertise, as Plamondon et al. (2014a, 2014b) demonstrated previously.

Knee posture appears to be related mostly by load mass and expertise (Table 7 in ♀**L**). Interestingly, females in this study were prone to bend their knees more at the beginning of the lift when the load was heavier (15 kg:Table 2A), probably to protect their back as they learned. This is not a characteristic of females only, as Sheppard et al. (2016) indicated that their participants (males and females) were bending the knees more at the start of the lifting when the load was heavier. They also showed a significant effect of load on lifting technique about the knee and ankle. Expertise must also be considered a factor in the lifting technique as experts (when the load is near the floor) had significantly more knee flexion at PRM than novices or females (Figure 4; Plamondon et al., 2014a,b).

Hands-L5/S1 distance in females increases with lighter boxes (Davis and Marras, 2000 and Faber et al., 2007) and appears to be influenced mainly by the load and expertise once distance is normalized. An increase in hands-L5/S1 distance could be seen as a negative effect on back loading; however, it could also ease the transfer of a box by leaving some space from the body in order to manoeuver the box. This is very difficult to do with heavy boxes when one has no choice but to keep the box close to the body in order to avoid a large moment at the back.

Relative phase angles between expert males and females (when lifting boxes from the bottom of the pallet) showed that females had a more sequential pattern in their interjoint coordination than experts, even with lighter boxes of 10 kg. Novice males were difficult to compare and classify for lack of any distinctive pattern. Expertise is certainly a factor here as experts and novices differ largely (Plamondon et al., 2014b). The interjoint coordination of females with the 10-kg boxes was more in phase than with the 15-kg boxes, but not sufficiently to be part of a cluster (Table 6). As mentioned in Plamondon et al. (2014b), the problem with the women's sequential lifting technique is that it tends to change a flexed squat lift (supposed to protect the back, as they learned) into a stoop lift, which might put large stresses on the lumbar spine in full flexion when boxes are lifted from near floor level. Whatever the load (10 or 15 kg), females were close to their full lumbar flexion at PRM (females 15 kg = 106%; female 10 kg = 102%; experts 15 kg = 84%). According to Dolan et al. (1994), many individuals can bend their lumbar spine by 110% or more of their static full range during dynamic movement of the upper body. Back muscles provide a margin of safety for the spine so that the point of injury would be at about 130% on the in vivo scale. Viscoelastic creep can also be involved during repetitive lifting. Nevertheless, several authors (Adams et al., 2002; Burgess-Limerick, 2003; McGill, 2007; Marras, 2008) have recommended avoiding such an extreme posture in flexion.

Numerous studies have investigated the coordination between lower extremity joints and the back in MMH and found that as the load weight increased, lumbar spine motion lagged further behind the lower extremity joint motion (Davis et al.,1965; Scholtz, 1993a, 1993b; Scholz et al., 1995; Burgess-Limerick et al., 1995). It was expected that a reduction of the load (from 15 to 10 kg) in females would decrease the sequential pattern in their interjoint coordination. It was the case, but not as much as expected. This suggests that the sequential lifting pattern is only partly related to the load and that a sex-specific technique is maybe used.

Plausible explanations for the difference in coordination between sexes lie in the hip extensors' relative flexibility compared to the spine extensors as well as in their relative strength compared to the back extensors, both being potentially greater in females than in males. While the presence of sex differences in the lumbar spine range of motion is not clear (Intolo et al., 2009), the pelvis maximal flexion is invariably higher in females (Peharec et al., 2007; Hoffman et al., 2012; Nelson-Wong et al., 2012; Larivière et al., 2014), which can facilitate greater pelvic motion in females than in males. On the other hand, Marras et al. (2003) indicated that females had adopted a lifting style that made more use of their hips, possibly due to their limited strength in the lumbar region. This would explain the technique they use in this study, which clearly demands more of the hip extensors than the technique used by the males. Though we found no data in the literature to support this hypothesis, we do have a database (11 women and 11 men) of maximum strength (static effort) of back extensor muscles and hip extensor muscles measured with a dynamometer, results not published in the original article (da Silva et al., 2009). Two positions were considered, both of which can be generalized to load lifting: (1) hip at 90°

and knee at 90°; and (2) hip at 90° and knee at 135°. The hip/back strength ratio was in fact higher ($p = 0.019$) in the women (1.10 ±0.21) than the men (0.91 ± 0.21), and the ratio (1.08 ± 0.19) was higher ($p = 0.003$) in position 2 than in position 1 (0.92 ± 0.25), confirming our hypothesis. This supports the technique used by the women, that is, straightening the knees (as in position 2) before lifting the load.

On the other hand, the 5-kg load difference between males and females was perhaps not enough to show a change in the lifting technique as our female participants had strength corresponding on average to 48% – 61% of the males' strength. Lifting technique is maybe not sex-specific, and future research should extend these findings to more distinct loads. Lastly, it is also possible that our experienced female workers had been working under the same conditions as males for several years and had to lift the same absolute load (boxes 17 kg on average). Therefore they developed a constant coordination pattern (sequential) that strengthens with time and because of this, it is possible that whatever the load lifted they will continue to use the same coordination pattern.

In summary, temporal variables and kinetic variables (moments) during lifting are mainly related to load mass; posture variables to load and expertise; and joint coordination parameters to load and perhaps sex. It appears from this study that expertise always interacts with load or sex during lifting, and this factor should not be neglected in future studies.

Limitations of the study. Apart from the limitations already mentioned in Plamondon et al. (2014a, 2014b), our experimental approach, designed to maximize external validity with the use of absolute loads (population approach), has not been conceived to jointly explain the roles of load, sex and expertise in the lifting technique used by females, which would have required more internal validity in the recruitment of our subjects, in the adjustment of loads to subjects' strength and in the adjustment of origin/destination heights to body stature (individual approach). This population approach (♂15 kg vs ♀10kg) may have impacted our findings by generating, within each group (males, females), variability in the results due to the handling of different individual relative loads. Fortunately, this variability was not so problematic since several between-group effects were still detected. We believe that on a group basis, the main findings that we observed in the present study should reflect an individual approach.

A second concern is whether fatigue confounded these findings. Measurements showed that fatigue showed may or may not differ according to load and sex, depending on the measure. Even though we have not observed large differences in fatigue development between the experimental conditions that were contrasted, this may have induced variability in the results and possible systematic differences.

5. Conclusions

It was hypothesized that the biomechanics of the lifting technique used by female workers would be equivalent to those of males when the relative load is similar (male 15-kg boxes and female10-kg boxes). This hypothesis proved true for some variables such as task duration and cumulative loading, and partially true for variables defining posture. The sequential interjoint coordination pattern previously seen in females with an absolute load (15 kg), when compared to expert males, was still present with the use of the same overall relative load (females 10 kg; males: 15 kg). This suggests that the sequential lifting pattern is probably not related to load only. A sex difference in the hip-extensors/back-extensors strength ratio is an alternative explanation, but remains to be tested. Considering that the sequential lifting pattern stretches the posterior passive tissues, potentially leading to higher risk of injury, the reason for this sex effect must be identified in order to propose preventive interventions.

Authors' contributions

All of the authors conceived and designed the study and prepared this manuscript. All of the authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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	Part 1: 15 kg-box condition Results in Plamondon et al. (2014b)								Rest 30 min	Part 2: 10 kg-box condition Current paper							
Group	Pre-test (0)		Self-paced transfer (T1)			Imposed-pace transfer (T2)				Pre-test (0)		Self-paced transfer (T1)			Imposed-pace transfer (T2)		
	EMG	B	T	EMG	B	T	EMG	B		EMG	B	T	EMG	B	T	EMG	B
Male	x		2x	x	x	3x	x	x		No males							
Female	x	x	2x	x	x	x	x	x	→	x	x	x	x	x	x	x	x

Figure 1. Schematic description of the experimental design: T=Transfer; x-2x-3x = number of times; EMG = EMG Test; B = Borg's assessment.

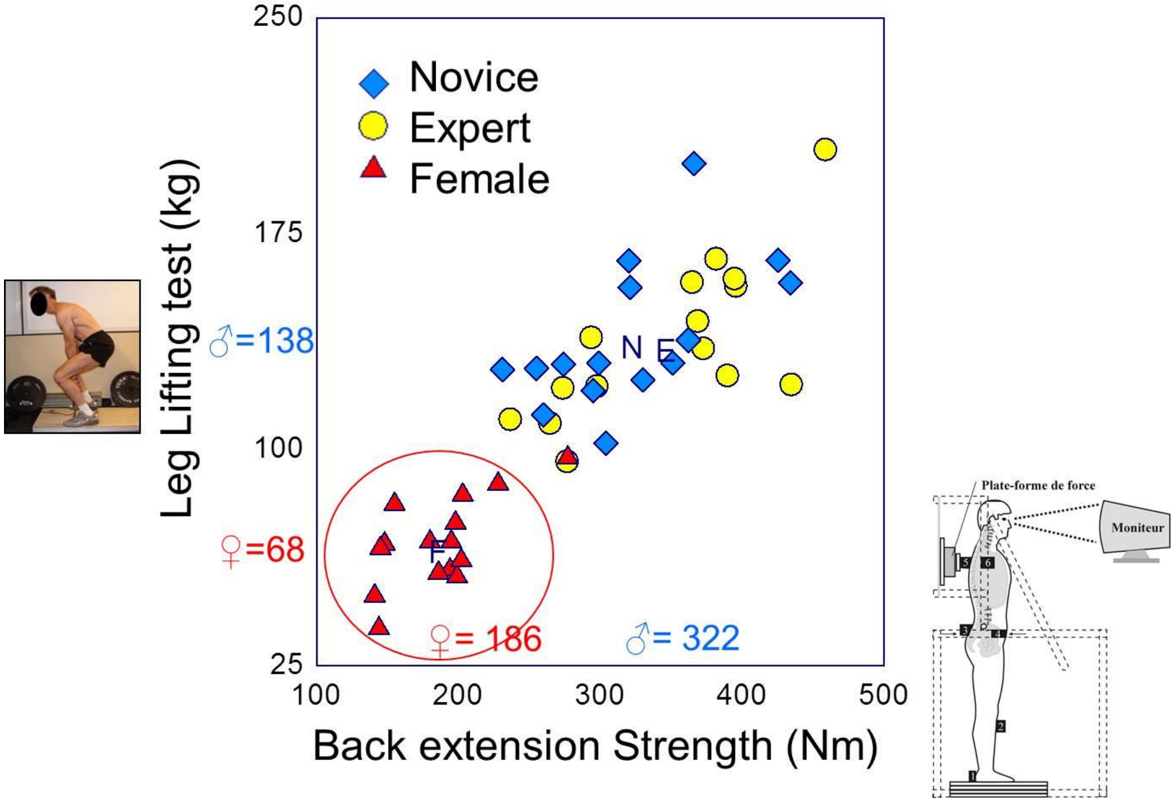

Figure 2: Physical isometric strength in experts (E), novices (N) and females (F) in the leg lifting test (kg) and in the back extension strength test (Nm). The average strength in the leg lifting was 138 kg for males and 68 kg for females; in the back extension, 322 Nm for males and 186 Nm for females.

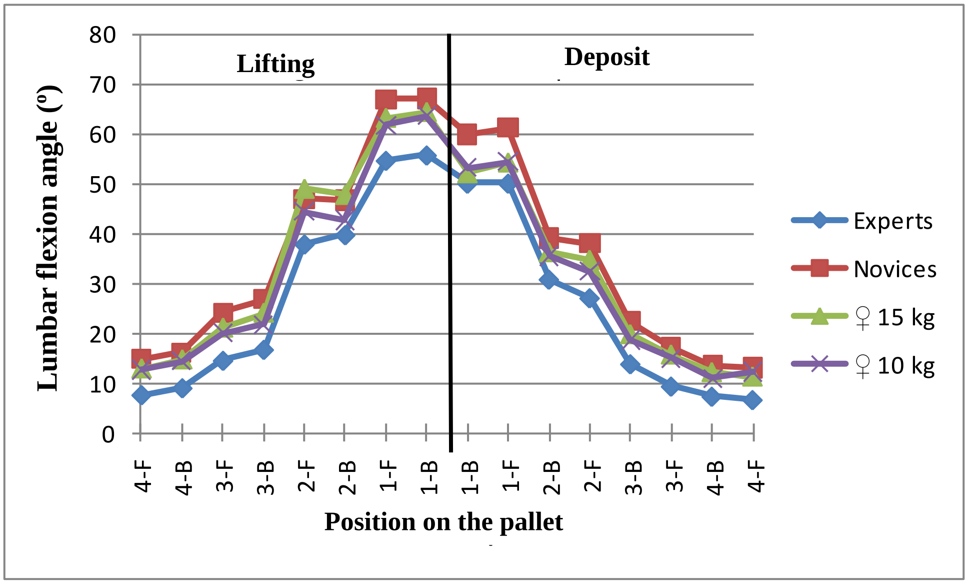

Figure 3: Lumbar flexion (degrees) at time of peak resultant moment for 15 kg and 10 kg conditions as a function of position on the pallet during lifting and deposit. Numbers 4, 3, 2 and 1 indicate vertical position of the boxes (1 = first layer – bottom of the pallet; 4 = fourth layer); letters F and B indicate horizontal position (front row and back row).

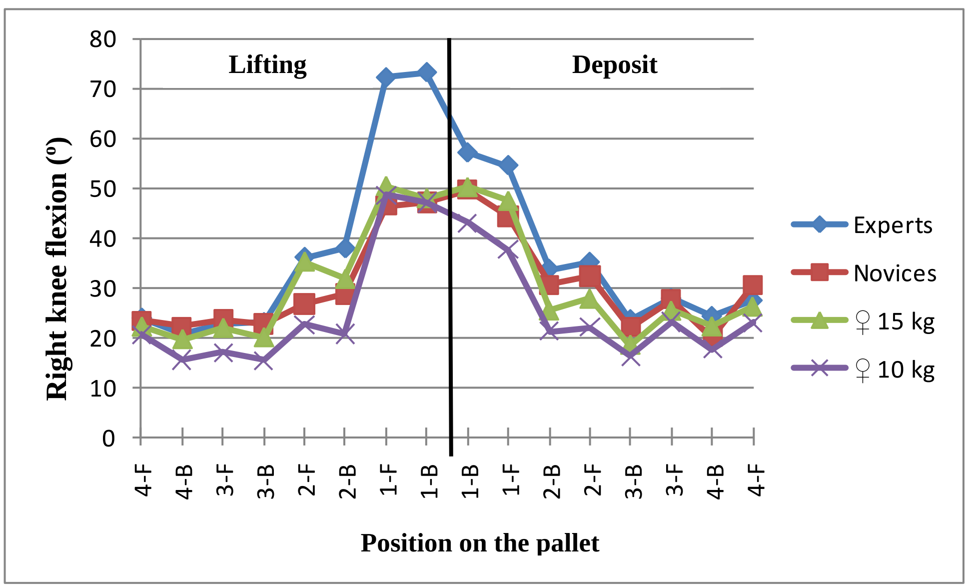

Figure 4: Right knee flexion (degrees) at time of peak resultant moment for 15 kg and 10 kg conditions as a function of position on the pallet during lifting and deposit (similar figure for left knee). Numbers 4, 3, 2 and 1 indicate vertical position of the boxes (1 = first layer – bottom of the pallet; 4 = fourth layer); letters F and B indicate horizontal position (front row and back row).

Table 1: Mean values and standard deviations for lifting pace, heart rate and fatigue with Borg scale (ψ). A) ♀L: Comparison between 10 kg and 15 kg in females; B) RL: Comparison between males 15 kg and females 10 kg

	A)♀L						**B) RL**			
Variables	10 kg		15 kg		Difference					
	M	SD	M	SD	Δ	*P*	Group	Pace	GP	Post-hoc*
Task duration (s)	4.7	0.9	5.7	1.8	-1.0	**<.01**	0.80	**<.01**	0.17	
Lifting pace (boxes/min)	9.2	0.7	8.2	1.3	1.0	**<.01**	0.86	**.04**	0.36	
General fatigue (ψ)	3.0	1.1	3.9	1.7	-0.9	**0.03**	**0.01**	**<.01**	**0.02**	F<E,N
Back fatigue (ψ)	3.0	1.6	3.4	2.4	-0.4	0.40	0.11	**<.01**	**<.01**	
Heart rate (bpm)	125	13	141	15	-16	**<.01**	**<.01**	**<.01**	**<.01**	F<E

*A posteriori tests when main effect of group (G) was significant: F = females; N = male novices; E = male experts;

Table 2: Peak resultant moment at L5/S1 and associated variables in the lifting phase (L) and deposit phase (D). A) ♀L: Comparison between 10 kg and 15 kg in females; B) RL: Comparison between males 15 kg and females 10 kg

Variables		**A)♀L**						**B) RL**				
		10 kg		15 kg		Difference		*p*	Interaction (*p*)			Post-hoc*
		M	SD	M	SD	Δ	*P*	G	GH	GD	GP	G
Peak resultant moment (Nm)	L	119	39	134	42	-15	**<0.01**	**<0.01**	**<0.01**	0.22	0.51	F < E,N
	D	95	39	112	42	-17	**<0.01**	**<0.01**	0.19	0.06	**0.02**	F < E,N
Lumbar flexion angle (°)	L	35	23	37	24	-2	**0.02**	0.06	0.58	0.70	0.38	
	D	29	20	29	20	0	0.45	**0.04**	0.72	0.43	0.57	E < N
Trunk inclination (°)	L	48	31	48	31	0	0.36	**<0.01**	**0.02**	0.93	0.37	F,N > E
	D	40	28	39	29	1	0.41	**<0.01**	0.88	0.45	**0.04**	F,N > E
Right knee flexion (°)	L	26	22	31	24	-5	**<0.01**	**0.01**	**0.01**	0.07	0.08	F < E
	D	25	18	30	22	-5	**<0.01**	**0.01**	0.55	0.42	**0.03**	F < E
Hands distance from L5/S1 (m)	L	0.37	0.08	0.35	0.08	.02	**<0.01**	**<0.01**	0.06	**0.04**	0.86	F,E < N
	D	0.39	0.12	0.35	0.12	.04	**<0.01**	**0.02**	0.28	0.08	0.18	F,E < N
Cumulative moment (Nms)	L	133	33	170	46	-37	**<0.01**	**<0.01**	0.51	**0.02**	**<0.01**	F < E,N

*A posteriori tests when main effect of group (G) was significant: F = females; N = male novices; E = male experts.

Table 3: Normalized moments at L5/S1 as well as box distances in lifting phase (L) and deposit phase (D). A) ♀L: Comparison between 10 kg and 15 kg in females; B) RL: Comparison between males 15 kg and Females 10 kg

Variables	Phase	A)♀L						B) RL				
		10 kg		15 kg		Difference		*p*	Interaction (*p*)			*Post-hoc**
		M	SD	M	SD	Δ	*p*	G	GH	GD	GP	G
Peak resultant moment[1]	L	1.70	0.51	1.91	0.57	-.21	**<0.01**	**0.03**	**<0.01**	0.21	0.63	F < N
	D	1.36	0.53	1.61	0.58	-.25	**<0.01**	**0.02**	0.27	0.08	**0.02**	F < N
Cumulative resultant moment[1]	L	1.90	0.45	2.44	0.68	-.54	**<0.01**	0.09	0.48	**0.02**	**<0.01**	
Hands distance from L5/S1at time of peak moment[2]	L	0.23	0.05	0.21	0.05	.01	**<0.01**	**0.05**	0.09	**0.05**	0.85	E < N
	D	0.24	0.07	0.22	0.07	.02	**<0.01**	0.14	0.23	0.19	0.18	

1. Normalization = Moment/ trunk gravitational moment; unit of trunk weight
2. Normalization = Distance/height; unit of height
*A posteriori tests when main effect of group (G) was significant: F = females; N = male novices; E = male experts

Table 4: Difference between maximum right knee angle (Max. angle) and angle at time of peak resultant moment at L5/S1 (angle at PRM) while lifting boxes from the pallet floor

Right knee variables	Females 10 kg		Females 15 kg		*p*
	M	SD	M	SD	
Max. angle (°)	65	37	79	36	**<.01**
Angle at PRM (°)	48	31	49	32	.072
Difference (°)	17	17	30	23	**<.01**

Notes: One way repeated ANOVA; boldface = $p < 0.05$

Table 5. Mean values (M) and standard deviations (SD) for the maximum amplitude of relative phase angle

Variables	Experts 15 kg (E)		Females 10 kg (F10)		Females 15 kg (F15)		*Prob p*[1]		
	M	SD	M	SD	M	SD	F10-F15	F10-E	F15-E
Right Knee/Hip	21	20	31	21	37	17	**<.01**	**<.01**	**<.01**
Right Hip/Back	32	17	45	18	53	16	**<.01**	**<.01**	**.01**

[1]One way repeated ANOVAs: boldface = $p < 0.05$

Table 6. Number of subjects classified into the three clusters with medoid clustering

Joint	Clusters	Females 10 kg	Females 15 kg	Experts 15 kg
Right Knee/Hip	All Mixed	5	4	4
	Mixed♀	7	8	0
	♂15	3	3	11
Right Hip/Back	All Mixed	5	5	3
	Mixed♀	6	7	3
	♂15	4	3	9
Left Knee/Hip	Mixed♀	5	7	2
	Mixed♀	7	8	1
	♂15	3	0	12
Left Hip/Back	All Mixed	3	7	5
	Mixed♀	8	8	0
	♂15	4	0	10

Notes: All Mixed = Expert males and females in the cluster; Mixed ♀ = Majority of females with the 10-kg and 15-kg boxes in the cluster; ♂15 = Majority of expert males in the cluster

Table 7: Main group effect (♀ = females, ♂ = males: E = experts, N = novices) found during the lifting phase (L) and deposit phase (D) and the possible causes (L = load, S = sex, E = expertise; major cause shown by capital letter)

	Variables		Load Female (♀**L**)	**R**elative **L**oad **(RL)**	**A**bsolute **L**oad[1] **(AL)**	Possible Cause
			10 kg vs 15 kg	♀vs♂	♀vs♂	
Time	Lifting pace	L	>	=	<	L
	Task duration	L	<	=	>	L
Moments	Peak resultant	L	<	<	<	l-s
		D	<	<	♀<N	l-s
	Cumulative	L	<	<	♀<N	l-s
Moments normalized	Peak resultant	L	<	♀<N	=	l-e
		D	<	♀<N	♀>E	l-e
	Cumulative	L	<	=	>	L
Posture at PRM	Lumbar flexion	L	<	=	=[2]	l-e
		D	=	=[2]	=[2]	E
	Trunk inclination	L	=	♀,N>E	♀,N>E	E
		D	=	♀,N>E	♀,N>E	E
	R. Knee flexion	L	<	♀<E	=[3]	l-e
		D	<	♀<E	=	l-e
Distance at PRM	Box distance	L	>	♀,E<N	<	l-e-s
		D	>	♀,E<N	<	l-e-s
	Normalized box distance	L	>	=	♀<N	l-e
		D	>	=	♀<N	l-e
	Joint coordination (Clusters)	L	≈	♀≠E ♀≠N	♀≠E ♀≠N	s-e

Note: PRM = Peak resultant moment

[1] Data from Plamondon et al. (2014b)

[2] In lumbar flexion ♀ = ♂, but experts ≠ novices (Figure 3)

[3] Experts bent their knee more at floor height (GxH <.05; Table 2; Figure 4).

Appendix A: Supplemental Data

The subject's perception of general physical fatigue and back muscle fatigue was assessed with a CR-10 Borg's scale (Borg, 1982). Heart rate (HR) was monitored with a polar system (model RS800; www.polar.fi). In addition, localized back muscle fatigue was evaluated during the experiment—at the beginning and after each pace condition—with a standardized isometric submaximal task using surface electromyography (EMG). The EMG tests were performed just before the start of the box transfer (0: Pre-test), after the self-paced transfer (T1) and after the imposed-pace transfer (T2) (see schematic description in Figure 1). The submaximal task (EMG tests) consisted in holding the trunk in a horizontal position for 5 s while lying prone on a roman chair. EMG was recorded at 1024 Hz with two pre-amplified electrodes (gain: 1000, model DE-2.3, Delsys, Boston, MA) placed bilaterally over the longissimus muscle (3 cm lateral to L3). The magnitude of the EMG signal was measured with a Root Mean Square (RMS) method with a moving average window of 100 ms. The median frequency was computed using the middle 3 s of the 5 s EMG signal period captured during the submaximal isometric contractions.

The mean HR was calculated for the two last going transfers (self-paced and imposed pace). Three Borg's assessments were recorded, each of them after the EMG test (see Figure 1). EMG fatigue includes the RMS and MF values of the right and left longissimus muscles for the three EMG tests. The EMG data for the females were evaluated with a two-way repeated ANOVA (2, 3): two loads: 10 kg vs. 15 kg; and three tests: pre-test, self-paced and imposed pace. The EMG differences between males and females were assessed with a two-way mixed factorial ANOVA (3, 3); G = three groups: experts, novices, females; and three tests: pre-test, self-paced and imposed pace. A significance level of $p < 0.05$ was used.

Fatigue before box transfer for females

This is to check whether the level of fatigue in females was similar at the start of the 15-kg and 10-kg box transfers (pre-test 15 kg vs. pre-test 10 kg; Figure 1). The perception of physical fatigue on the Borg CR10 scale just before the 15-kg transfers was 0.7 (SD = 0.8) (just above "0.5 extremely weak" and below "1.0 very weak") and the mean value before the 10-kg transfers was 1.6 (SD = 1.0) (below "2.0 weak"). This difference was significant, but on the other hand, the perception of fatigue was less than "weak". Moreover, EMG parameters indicate no difference in the EMG fatigue state of the back muscles (*longissimus*) at the beginning of the 15-kg or 10-kg box transfers (Table A1). Therefore the level of fatigue before the transfers was weak.

Progression of females' muscle fatigue during the transfer of 10 and 15-kg boxes

The EMG RMS parameters increased while the EMG MF parameters decreased from one test to the next, which is consistent with the progression of muscle fatigue, although only two of the four parameters reached statistical significance (Table A1; Test). The effect of load was not significant, but the Load × Test reached statistical significance for the Right longissimus (RMS and MF). These interactions indicate that the progression of fatigue was faster with the 15-kg boxes from the start (pre-test) to the self-paced condition, then nearly stabilized until the end.

Progression of muscle fatigue of males (novices and experts; 15 kg) and females (10 kg) during box transfers simulating the same RL

All four EMG parameters showed significant changes that are consistent with the progression of muscle fatigue (Table A.2). One interaction (G×T; Right longissimus) reached statistical significance and indicates that fatigue was slower among females (10-kg boxes) from the start to the self-paced condition, increasing slowly until the end. We have previously shown (Plamondon et al., 2014b) that the level of fatigue with the 15-kg boxes was equivalent between the groups even if the females did only one trip under the imposed pace condition as opposed three for the males. The level of fatigue (perception and EMG) of females during the transfer of the 10-kg boxes indicates that it was slightly lower than with the 15-kg boxes (Table 1A) and also lower in comparison to males (Table 1B).

Table A.1. EMG results for females: Back muscle fatigue of the Left (L) and Right (R) Longissimus evaluated three times (1 – pre-test; 2 - after self-paced; 3 - after imposed pace) during the transfer of 15-kg and 10-kg boxes

Variables	Pre-test		Self-paced		Imposed Pace		*P value*		
	10 kg	15 kg	10 kg	15 kg	10 kg	15 kg	Load	Test	L×T
L Back - RMS	.080 (.066)	.067 (.037)	.087 (.065)	.074 (.056)	.089 (.065)	.080 (.053)	.29	.13	.89
L Back - MF	72 (10)	74 (11)	71 (10)	71 (13)	69 (11)	68 (12)	.58	**.02** $^{1>3}$	.55
R Back - RMS	.089 (.044)	.075 (.030)	.091 (.048)	.098 (.050)	.098 (.057)	.101 (.047)	.84	**<.01** $^{1<2-3}$	**<.01**
R Back - MF	72 (13)	76 (11)	72 (13)	70 (14)	70 (14)	71 (14)	.46	.10	**.03**

Note: RMS = root mean square (mV); MF = median frequency (Hz); Significant interaction LxT indicates that females tended to fatigue faster with the 15-kg boxes between the pre-test and the self-paced test.

Table A.2. Mean values and standard deviation (in parentheses) in fatigue results for the longissimus muscles between experts (E-15kg), novices (N-15kg) and females (F-10kg) (n = 45)

Variables	Pre-test (0)			Post-test (1)			Post-test (2)			Probability			*Post Hoc* P
	E	N	F	E	N	F	E	N	F	G	T	G×T	
RMS Long L (mV)	.096 (.047)	.128 (.056)	.080 (.066)	.115 (.053)	.152 (.067)	.087 (.064)	.126 (.064)	.181 (.118)	.089 (.065)	n.r.	**<.01**	0.19	0<1<2
MF Long L (Hz)	85 (19)	91 (17)	72 (10)	79 (15)	82 (17)	71 (10)	76 (15)	80 (20)	69 (11)	n.r.	**<.01**	0.26	0>1,2
RMS Long R (mV)	.092 (.044)	.143 (.091)	.089 (.043)	.109 (.050)	.154 (.095)	.091 (.048)	.113 (.055)	.177 (.122)	.098 (.057)	n.r.	**<.01**	0.19	0<1,2
MF Long R (Hz)	85 (15)	94 (19)	72 (13)	81 (16)	83 (18)	72 (13)	77 (12)	82 (21)	70 (14)	n.r.	**<.01**	**<.01**	0>1,2

Notes: RMS = root mean square (mV); MF = Median power frequency of the left (L) or right (R) longissimus muscle (Long); G = Groups: Experts, Novices, Females ; T = Tests: 0,1,2; GT = Group × Test interaction; post-hoc test for Tests (T); n.r. = not relevant; boldface = $p < 0.05$