Sex differences in upper limb 3D joint contributions during a lifting task

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*Abstract*: Sex-related differences in work technique may contribute to increase the risk of injuries among women. In lifting tasks, sex differences have been reported for the trunk and lower limb, although women present a higher prevalence of shoulder disorders. We investigated sex differences in the upper limb technique during a lifting task. Trunk and upper limb kinematics were recorded in 27 women and 27 men lifting a box (6 or 12 kg) between two shelves (hip and eye levels). Work technique was quantified through the three-dimensional contribution of each joint to overall box height. The glenohumeral joint showed a higher contribution in women with a 6 kg box and wrist and elbow joints did with a 12 kg box, compared to men at either 6 or 12 kg. Sex differences occurred systematically above shoulder level. Our results argue for a careful consideration of sex during ergonomic intervention, particularly during overhead task.

*Practitioner Summary*: We investigated the sex-related differences in upper limb technique during lifting tasks. Results highlight a sex-specific kinematic strategy above the shoulder level on the glenohumeral joint and on the wrist and elbow joints. To help reduce women’s shoulder disorders in overhead task, ergonomic interventions should account for those differences.

*Keywords*: sex differences; upper limb kinematics; lifting task; joint contribution; work techniques.

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# Introduction

Musculoskeletal disorders represent the most common form of work disability (European Agency for Safety and Health at Work [2010](#ref-europeanagencyforsafetyandhealthatwork_osh_2010); Punnett and Wegman [2004](#ref-punnett_workrelated_2004); US Department of Labor [2016](#ref-usdepartmentoflabor_nonfatal_2016)). Shoulder disorders are the first cause of work-related musculoskeletal disorders after back pain, with a reported prevalence up to 35% in Europe (Luime et al. [2004](#ref-luime_prevalence_2004); Urwin et al. [1998](#ref-urwin_estimating_1998)). The occurrence of shoulder injuries has been associated with work factors such as overhead work, heavy lifting, repetitive movements and poor postures (Bernard [1997](#ref-bernard_musculoskeletal_1997); Grieve and Dickerson [2008](#ref-grieve_overhead_2008); Latko et al. [1999](#ref-latko_crosssectional_1999)), but also with individual risk factors such as sex (Häkkänen, Viikari-Juntura, and Martikainen [2001](#ref-hakkanen_job_2001)). While women are underrepresented in manual material handling work, the prevalence of their upper extremity injuries is greater than in men (de Zwart, Frings-Dresen, and Kilbom [2001](#ref-dezwart_gender_2001); Nordander et al. [2008](#ref-nordander_gender_2008); Punnett and Herbert [2000](#ref-punnett_workrelated_2000)).

Sex differences in the onset of musculoskeletal disorders are commonly associated to sex-specific physical differences Anthropometry, muscular histological composition and strength differences are among the most cited, especially for the upper limb (see Côté [[2012](#ref-cote_critical_2012)] for a review). Differences in motor behavior such as work technique between women and men have also been identified and may contribute to the increased risk of upper limb musculoskeletal disorders among women (Côté [2012](#ref-cote_critical_2012)). However, a sex difference in work technique is rarely addressed in the literature, even if it is well known that it represents a risk factor associated with musculoskeletal disorders (Kilbom and Persson [1987](#ref-kilbom_work_1987)). Work techniques are commonly simplified by a set of postures adopted during a task (Potvin [2008](#ref-potvin_occupational_2008)). This definition is insufficient to understand the biomechanics of a dynamic movement. Instead, joint coordination has been suggested as a key element for the description of lifting techniques (Burgess-Limerick et al. [1995](#ref-burgess-limerick_selfselected_1995)). Previous studies identified sex differences in trunk and lower limb joint coordination during manual handling tasks with absolute (Plamondon et al. [2014](#ref-plamondon_sex_2014)) and relative loads (Plamondon et al. [2017](#ref-plamondon_difference_2017)). More particularly, work techniques were similar among men and women in terms of task duration and cumulative loading, but differences appeared in joint coordination. Another recent study attributed differences in lifting coordination amongst women to differences in strength (Yehoyakim et al. [2016](#ref-yehoyakim_relationship_2016)), suggesting that strength could also underlies sex differences in lifting coordination. However, a large majority of studies have focused on the back and lower limb and the sex-specific contribution of the upper limb’s joints during a lifting task remains unknown.

The objective of this study was to investigate how the upper limb joints’ contributions differ between men and women performing a lifting task. In accordance with biological differences and sex differences in trunk and lower limb coordination previously reported, we hypothesised that women would use a different upper limb joint contribution strategy to perform a lifting task than men.

# Methods

## Participants

In total, 27 women (21.391.79 years; 167.796.66 cm; 61.397.89 kg) and 27 men (25.635.72 years; 178.597.32 cm; 74.5610.77 kg) took part in this study. None of the participants were ever diagnosed with musculoskeletal disorders of the upper limbs or reported significant disability related to their upper extremity (Disabilities of the Arm, Shoulder and Hand scores >23, Hudak, Amadio, and Bombardier ([1996](#ref-hudak_development_1996))) or their back (Quebec Back Pain Disability Scale score <3, Kopec et al. ([1995](#ref-kopec_quebec_1995))). Readiness for physical activity was confirmed in all participants (Physical Activity Readiness Questionnaire, Thomas, Reading, and Shephard ([1992](#ref-thomas_revision_1992))). The participants were fully advised of the experimental content, and each of them provided a written informed consent. The study was approved by the University of Montreal Ethics Committee (No. 15-016-CERES-P).

## Experimental Procedures

A static trial and setup movements in line with previous recommendations (Begon, Monnet, and Lacouture [2007](#ref-begon_effects_2007); Michaud et al. [2016](#ref-michaud_determining_2016)) were acquired to locate the joint centres and personalize a kinematic model (Jackson et al. [2012](#ref-jackson_improvements_2012)). Then, participants moved an instrumented box between two adjustable shelves located directly in front of them. Shelf heights were adjusted at the hip and eye levels of each participant. The box (height  width  length: 0.08 m  0.35 m  0.50 m) had two symmetrical handlebars to standardise the grip. We set the box mass at 6 kg and 12 kg, which corresponds to the maximum acceptable mass in our configuration (box length: 0.50 m, vertical distance of lift: 76 cm, frequency of two boxes per minute) for 90% of female and male respectively (Snook and Ciriello [1991](#ref-snook_design_1991)). Each participant used the two masses (6 and 12 kg). The right handle of the box was instrumented with a 6-degree-of-freedom force sensor (Sensix SH2653-1106B3, Poitiers, France), used to determine the beginning and end of the trial in the present study.

Participants were instructed to move the box from the hip to the eye level at a comfortable speed and to minimise the movements of their lower limbs. No other instructions on work technique were given. Three repetitions of movements were performed for each mass (three trials with 6 kg and three with 12 kg) in a random order with 30 s rest periods in-between. Additional recovery time was allowed when needed. The lifting movement was split into three phases, namely the pulling (1-20% of the trial duration), lifting (21-60%) and dropping (61-100%) phases (Fig. 1).

[Insert figure 1 here]

## Data Collection

Movement kinematics were recorded with an 18 VICONTM camera motion analysis system (Oxford Metrics Ltd, Oxford, UK) at a sampling rate of 100 Hz. In line with the kinematic shoulder model of Jackson et al. ([2012](#ref-jackson_improvements_2012)), 43 reflective markers were placed on the pelvis, trunk and right upper limb (Fig. 2): pelvis (4 markers), thorax (6), clavicle (6), scapula (8), upper arm (7), forearm (4), wrist (4) and hand (4). This marker set includes anatomical markers located on bony landmarks for the model definition and technical markers located in areas that minimised skin movement artifacts for joint kinematics estimation during lifting trials. Assuming that the left and right sides of the upper body behaved symmetrically during a symmetrical box lifting task (Nielsen, Andersen, and Jørgensen [1998](#ref-nielsen_muscular_1998)), only the right side of the participant was evaluated.

[Insert figure 2 here]

## Data Processing

A 25 degree-of-freedom (DoF) kinematic model was personalized using the static trial (pelvis and trunk [6 DoF each], sternoclavicular and acromioclavicular [3 DoF each], glenohumeral [3 DoF], elbow and wrist [2 DoF each]). Centres of rotation of the pelvis, trunk, and wrist joints were located using the SCoRE algorithm (Ehrig et al. [2006](#ref-ehrig_survey_2006)), while bony landmarks were used for locating sternoclavicular, acromioclavicular and glenohumeral joints, in agreement with recent recommendations (Michaud et al. [2016](#ref-michaud_determining_2016)). Elbow flexion and prosupination axes were defined using the SARA algorithm (Ehrig et al. [2007](#ref-ehrig_survey_2007)). The reference configuration () of the pelvis, trunk, sternoclavicular and acromioclavicular were concordant with the ISB recommendations (Wu et al. [2005](#ref-wu_isb_2005)). The reference configurations of the glenohumeral, elbow and wrist joints were defined such that:

* glenohumeral and elbow longitudinal local axes aligned with that of the trunk;
* glenohumeral, elbow and wrist mediolateral local axes aligned with that of the scapula.

To overcome the covariance within each joint, lifting techniques were quantified through the individual joint contribution to the box height. The algorithm 1, inspired by the recent study of Robert-Lachaine et al. ([2015](#ref-robert-lachaine_elucidating_2015)) on scapulohumeral rhythm was applied. The contribution of each joint () to the box height was computed by successively resetting joint angles to their reference orientations (). Joint contribution refers to the amount of box height achieved by each group of joints, namely pelvis-trunk; sternoclavicular-acromioclavicular joints; glenohumeral joint; and elbow-wrist joints (Algorithm 1).

Algorithm 1. Calculation of the pelvis-trunk (PE/TR), sternoclavicular-acromioclavicular (SC/AC), glenohumeral (GH) and elbow-wrist (WR/EL) contributions. At time :

As the heights of the shelves were adjusted according to the anthropometry of each participant, box height was normalised to participant’s hip (0%) and eye (100%) levels to compare participants’ joint contribution. Data were delimited so that each trial began and ended when participants first applied, and first ceased to apply force on box handles, respectively. Then each trial was time normalized to 1000 data points.

## Statistics

To avoid reducing the joints’ contribution to a discrete value, contributions of men’s and women’s joints were compared using statistical parametric mapping with the spm1d package (Pataky [2010](#ref-pataky_generalized_2010)). A two-way ANOVA (, with repeated measures on mass) was applied for each group of joints. Sex-related differences in joint contribution were then compared using two-sample t-tests for the same absolute box mass (women at 6 kg *vs.* men at 6 kg and women at 12 kg *vs.* men at 12 kg) and relative box mass(women at 6 kg *vs.* men at 12 kg and women at 12 kg *vs.* men at 6 kg). The effect of mass on joint contributions for each sex was also analysed with paired-sample t-tests. Bonferroni corrections were applied across the six post-hoc tests (). A Pearson’s linear correlation coefficient was finally computed between the mean joint contribution of men and women against the relative mass of the box (box mass divided by participant mass).

# Results

## General Description of Joint Contribution to Box Lifting

Participants used mainly their distal joints (wrist and elbow) during the pulling and early lifting phases. Then, glenohumeral, sternoclavicular and acromioclavicular contributions increased during the second half of the lifting phase and plateaued during the dropping phase (Fig. 3). On average, pelvis and trunk have low contributions to the box height during the pulling (1%), lifting (2%) and dropping phases (8%). The contribution of the sternoclavicular and acromioclavicular joints increases over time, starting at -3% (*i.e., shoulder depression*) on the pulling phase, to 11% on the lifting phase and 33% on the dropping phase. The contribution of the glenohumeral joint also increases over time, starting at 12% on the pulling phase, to 28% on the lifting phase and 75% on the dropping phase. The contribution of the wrist and elbow joints starts at 14% during the pulling phase, peaks at 41% during the lifting phase and decreases at 7% during the dropping phase.

[Insert figure 3 here]

## Sex and Mass Effect on Joint Contribution

### Sex-Mass Interaction

There was a sex-mass interaction (Fig. 4, upper panel) on the contribution of the glenohumeral joint from 55% to 72% of the trial () and wrist and elbow joints from 63% to 69% of the trial ().

### Sex and Mass Main effect

There was no main effect of sex on the contribution of the selected joints (Fig. 4), lower panel) but significant main effects of the mass were identified on the trunk-pelvis, glenohumeral and wrist-elbow joints (Fig. 4), middle panel). The contribution of the pelvis and trunk was greater when men and women handled the heaviest mass from 45% to 99% of the trial (). For the glenohumeral joint, a significant main effect of mass was observed from 1% to 8% of the trial () and from 44% to 93% (), suggesting a greater glenohumeral contribution for the 6 kg box. The wrist and elbow joints contributed more when participants handled the 12 kg mass from 1% to 7% of the trial (), from 44% to 53% () and from 61% to 72% (). The main effect of mass for the wrist, elbow and glenohumeral joints are uninterpretable on the range of the concurrently significant interactions (Fig. 4), hatched lines on the lower panel).

[Insert figure 4 here]

### Post-Hoc Analysis

When comparing men at 12 kg against men at 6 kg and women at 12 kg against women at 6 kg in the time periods where significant sex-mass interactions were observed, differences appear only in women (Fig. 5). These differences occur on the glenohumeral joint (from 54% to 71% of the trial, ) with a contribution of about 20% higher with 6 kg compared to 12 kg, and the wrist and elbow joints (from 62% to 68% of the trial, ) with a contribution of about 9% higher with 12 kg compared to 6 kg.

[Insert figure 5 here]

In line with this finding, sex-related differences revealed by the post-hoc analysis are mainly dependent of the mass lifted by women (Fig. 6). On the glenohumeral joint, these differences have an opposite sign whether women lifted 6 or 12 kg. Indeed, when comparing women at 6 kg against men at 6 kg or 12 kg, the contribution of the glenohumeral joint is approximately 14% higher in women compared to men (from 54% to 71% of the trial, and for men at 6 and 12 kg, respectively). Whereas this contribution is approximately 10% higher in men compared to women when comparing women at 12 kg against men at 6 kg (from 59% to 71% of the trial, ) or 12 kg (from 63% to 68% of the trial, ). On the wrist and elbow joints, post-hoc analysis (Fig. 6) revealed sex-related differences only when women lifted a 12 kg box. These differences appeared against men at 6 kg (from 62% to 68% of the trial, ) or 12 kg (from 62% to 68% of the trial, ), with a contribution of about 8% higher in women compared to men.

[Insert figure 6 here]

## Correlation of the Joint Contribution Against the Normalized Mass

There was no significant correlation between the contribution of the glenohumeral, wrist and elbow joints and the relative mass of the box (Fig. 7) at 6 kg for men (wrist and elbow joint: , glenohumeral joint: ) and women (wrist and elbow joint: , glenohumeral joint: ). This correlation was also non-significant at 12 kg in men (wrist and elbow joint: , glenohumeral joint: ). However, there was a positive correlation at 12 kg in women on the wrist and elbow joints () and a negative correlation on the glenohumeral joint (). Since there was no sex-mass interaction on the trunk, sternoclavicular and acromioclavicular joints, correlations on these joints are not reported. Correlation are reported if there is a sex-mass interaction (trunk, sternoclavicular and acromioclavicular joints are not reported). Thus, when the mass of the box represents a greater proportion of the participant’s mass (the participant is lighter or the box is heavier), there is no change among men while women use more the wrist and elbow joints and less the glenohumeral joint.

[Insert figure 7 here]

# Discussion

## Main Finding

In accordance with our hypothesis, our results support the perspective of a sex-specific joint contribution strategy of the upper limb during a lifting task. In particular, this strategy seems to be influenced by the mass lifted by women. At 6 kg, women proportionally used more their glenohumeral joint than men. However, sex differences for this joint contribution were in the opposite direction at 12 kg, where men’s glenohumeral joint contributed more than women’s. This decrease in women’s glenohumeral contribution for the higher mass was compensated with the wrist and elbow joints. Similar differences appeared when normalizing the mass of the box by the participant’s mass. Most of the reported differences occurred during the dropping phase, when the arms are at shoulder level and above.

## Description of the lifting technique

### General Description

Our results show that participants had more contribution with their distal joints (wrist and elbow) during the first half of the movement while proximal joints (trunk, pelvis, sternoclavicular and acromioclavicular joints but particularly the glenohumeral joint) contributed more during the second half of the movement. We can hypothesise that participants use their distal joints to bring the box closer to the trunk during the pulling and the first half of the lifting phase, while the proximal joints are used to initiate and finish the arm elevation during the rest of the movement. Thus, there is a different joint contribution strategy depending on the phase of the movement.

### Sex-Related Differences

Despite the general joint strategy described above, our results highlight sex-related differences in lifting strategy. The glehumeral joint contributes more when women lift a 6 kg box and less when they lift a 12 kg box, compared to men at either 6 or 12 kg. The reduction of the glenohumeral contribution with a 12 kg box in women is compensated by a higher contribution of the wrist and elbow joints.

Other studies evaluating sex differences on participants’ joint coordination during manual handling focused on the back and lower limb. For instance, differences in lower limb joint coordination patterns were found, with a more sequential pattern of interjoint coordination in women than in men with both absolute (Plamondon et al. [2014](#ref-plamondon_sex_2014)) and relative loads (Plamondon et al. [2017](#ref-plamondon_difference_2017)). It is difficult to directly compare our results with those previous studies as different levels of expertise, joints, metrics and lifting height were studied. However, it is interesting to highlight that sex differences observed in the current study were only apparent when the box was higher than participant’s shoulder height, a situation not studied previously. Taken together, these studies suggest sex difference in lower-limb and trunk coordination when a box is lifted from the floor and in upper-limb coordination when the box is handled above shoulder level.

## Load May Explain Sex-Related Differences

Mass-related comparisons have demonstrated that women’s contributions of the glenohumeral, wrist and elbow joints are more affected by a change in the box mass from 6 to 12 kg than men’s. Sex-related comparisons were made with different mass ratios (): 50% (men at 12 kg *vs.* women at 6 kg), 100% (men at 6 kg *vs.* women at 6 kg and men at 12 kg *vs.* women at 12 kg) and 200% (men at 6 kg *vs.* 12 kg). However, it appears that the absolute mass manipulated by women was more important than those mass ratios to explain observed sex differences in joint contribution. When women lifted the 6 kg box, they used more their glenohumeral joint than men (mass ratios: 50% and 100%). When they lifted the 12 kg box, their glenohumeral joint contributed less than men (mass ratios: 100% and 200%). This effect was not observed by Plamondon et al. ([2014](#ref-plamondon_sex_2014)) and Plamondon et al. ([2017](#ref-plamondon_difference_2017)) studying the lower limb and trunk coordination, who found similar sex-related differences between equivalent absolute and relative load. However, these results are reminiscent of those of Yehoyakim et al. ([2016](#ref-yehoyakim_relationship_2016)) who found, in their study on women only, that the weight lifted had an impact on lifting coordination patterns. Together, these studies suggest that the guidelines on lifted weight have an especially important potential to affect women, more so than men.

Women may indeed be more influenced by the 6 kg variation (between 12 and 6 kg) than men because it represents a higher fraction of their body mass (10% in our sample) than men (8%). When lifting the 12 kg box, women are closer to their maximal muscle capacity. Moreover, significant correlations between the joint contribution and the relative mass of the box appear only in women lifting a 12 kg box, where heavier, and probably stronger (Barbat-Artigas et al. [2013](#ref-barbat-artigas_sexspecific_2013)) women use more the wrist and elbow joints and less the glenohumeral joint.

It is likely that kinematic adaptations occur in a non-linear manner with increased load: more important adaptations may occur when efforts are closer to maximal capacity. In line with this idea, it has been suggested that increasing the lifting load may change the coordination to reduce the required muscular effort (Burgess-Limerick et al. [1995](#ref-burgess-limerick_selfselected_1995)). Yehoyakim et al. ([2016](#ref-yehoyakim_relationship_2016)) have also highlighted the importance of strength on kinematic coordination. They showed a more coordinated movement between the hip and the back during box lifting in women with higher strength capabilities. If the fact that the heaviest box being closer to women’s maximal force explains the sex-specific adaptations with increased box mass, it would be expected that similar adaptations would also be observed when men handle objects heavier than 12 kg. However, even a with a 18 kg box, such an adaptation was not observed in our male subjects (see appendix 1). To fully understand this issue, it would be interesting to measure men’s and women’s maximal strength and verify at which relative load changes in joint contribution can be observed for each sex. Alternatively, the assessment of the relationship between electromyographic activity (normalized to maximal muscle contraction) generated during lifting and the changes in joint contribution could be informative. While sex differences in strength could explain the lower contribution of the glenohumeral joint when women lift the 12 kg box as exposed above, it can hardly cause the higher contribution of this joint when they lift the 6 kg box. This pattern of result suggests that other factors also contribute to the different motor strategies when men and women lift boxes above their shoulders. Anders et al. ([2004](#ref-anders_activation_2004)) demonstrated that women showed less activation of agonist muscles and greater activation of synergist muscles than men, during an isometric shoulder task to fatigue. Muscular coordination and a different shoulder-elbow strength ratio could play a role in explaining sex differences in motor behavior.

## Joint Contribution and Upper Limb Injuries

The reported differences occur systematically when the box is near or above the shoulder level, *i.e.* when the glenohumeral contribution is the highest. The overhead posture is considered as a risk factor for shoulder injuries (Grieve and Dickerson [2008](#ref-grieve_overhead_2008)) and the leading cause of rotator cuff tears (Vecchio et al. [1995](#ref-vecchio_shoulder_1995)). Epidemiological studies have shown that women work more frequently and during longer times with their hands above shoulder height than men (Dahlberg et al. [2004](#ref-dahlberg_work_2004)). In addition to longer working time in overhead position, we showed that women reach this position with a technique that mainly involves the glenohumeral joint with light masses and the wrist and elbow joints with heavier masses. In addition, women have more glenohumeral joint laxity and instability than men (Borsa, Sauers, and Herling [2000](#ref-borsa_patterns_2000)). This hypermobility may increase the risk of subacromial impingement as the subacromial space width is smaller in women (Graichen et al. [2001](#ref-graichen_sexspecific_2001)). Further work is needed to assess the sex-related differences in subacromial space during lifting tasks. We suggest that musculoskeletal modeling of the upper limb during a lifting task could help to understand the impact of those kinematic differences on the load applied to the upper limb structures.

## Ergonomics Applications

The kinematic analysis presented in this paper on joint contributions has enabled the evaluation of the upper limbs to the overall lifting technique. This parameter could be an ergonomic tool to identify poor techniques, which can lead to shoulder injuries. In this study, joint contribution has been determined with a motion analysis system. However, portable tools can be used such as inertial measurement units (Kim and Nussbaum [2013](#ref-kim_performance_2013)) to quantify physical exposures in the workplace.

While it is recognized that the work environment is often not adapted to women considering anthropometric sex differences (Pheasant and Haslegrave [2006](#ref-pheasant_bodyspace_2006)), we designed our experimental task to avoid such bias and the difference in joint contribution was still significant. It is important to remember that sex differences occur mostly above shoulder levels in our study. It is safe to say that those differences would probably be amplified in the workplace, where shelves would be proportionally higher for women.

Sex differences in health must be regarded as a multicausal phenomenon and work technique is one of the many factors which contribute in a complex interaction to explain sex-related differences in injuries (Côté [2012](#ref-cote_critical_2012)). The present study brings more depth to upper limbs motion analysis and demonstrates that overhead lifting techniques differ between men and women. The implications of such results argue that lifting technique should be considered with care during lifting task, especially in women who tend to work more frequently in overhead posture (Dahlberg et al. [2004](#ref-dahlberg_work_2004)). A careful consideration of sex during ergonomic interventions and research studies focusing on the upper limb are also recommended.

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# 

# Appendices

[Insert appendix 1 here]

# Figure captions

Figure 1. The three phases of a hips-eyes lifting movement: the pulling (1-20% of the trial duration), lifting (21-60%) and dropping phases (61-100%).

Figure 2. Positions of the reflective markers according to Jackson et al. ([2012](#ref-jackson_improvements_2012)). Note: the electromyography sensors visible on the figure were not used in the present study.

Figure 3. Mean (plain lines) and standard deviation (shaded areas) joint contributions over the time of the trunk and pelvis (TR/PE), sternoclavicular and acromioclavicular joints (SC/AC), glenohumeral joint (GH), and wrist and elbow joints (WR/EL) to the box height. All variables (sex and mass) are averaged.

Figure 4. Significant effects found by the statistical parametric mapping (ANOVA) on the interaction sex-mass, sex main effect and mass main effect for the trunk and pelvis (TR/PE), glenohumeral joint (GH), and wrist and elbow joints (WR/EL). No significant effects were observed for the sternoclavicular and acromioclavicular joints. Each segment represents a supra-threshold clusters over the normalized time. On the mass main effect panel, a color gradient is associated with the amplitude of the mass-related difference (blue when the contribution with the 6 kg box is higher, red when the contribution with the 12 kg box is higher). The hatched lines represent an uninterpretable main effect since an interaction is also present on the same range.

Figure 5. Joint contribution and post-hoc analysis for the two mass-related comparisons (left: men at 6 kg vs. men at 12 kg, right: women at 6 kg vs. women at 12 kg). Each comparison has two panels. The upper panel represents the post-hoc analysis where each segment represents a supra-threshold clusters over the normalized time, with a color gradient associated with the amplitude of the mass-related difference (green when the contribution with the 6 kg box is higher, orange when the contribution with the 12 kg box is higher). The lower panel represents the joint contribution of men and women over the time for the trunk and pelvis (TR/PE), sternoclavicular and acromioclavicular joints (SC/AC), glenohumeral joint (GH), and wrist and elbow joints (WR/EL).

Figure 6. Joint contribution and post-hoc analysis for the four mass-related comparisons (men at 6 kg vs. women at 6 kg on the top left panel, men at 12 kg vs. women at 6 kg on the top right panel, men at 6 kg vs. women at 12 kg on the bottom left panel, men at 12 kg vs. women at 12 kg on the bottom right panel). Each comparison has two panels. The upper panel represents the post-hoc analysis where each segment represents a supra-threshold clusters over the normalized time, with a color gradient associated with the amplitude of the sex-related difference (blue when men’s contribution is higher, red when women’s is higher). The lower panel represents the joint contribution of men and women over the time for the trunk and pelvis (TR/PE), sternoclavicular and acromioclavicular joints (SC/AC), glenohumeral joint (GH), and wrist and elbow joints (WR/EL).

Figure 7. Scatter plot of the mean joint contribution during the dropping phase (Y axis) of men and women against the relative mass of the box (X axis) for the wrist and elbow joints (WR/EL) and the glenohumeral joint (GH). A generalized linear regression model was fitted on each grouping variable (plain line) and the corresponding Pearson’s linear correlation coefficient is displayed at the top of the figure.

Appendix 1. Joint contribution of men (18 kg) and women (6 kg) over the time for the trunk and pelvis (TR/PE), sternoclavicular and acromioclavicular joints (SC/AC), glenohumeral joint (GH), and wrist and elbow joints (WR/EL). This sex-related comparison was not included in the statistics to keep a balanced design, as men lifted three masses (6, 12 and 18 kg) while women lifted two masses (6 and 12 kg).