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Handle height and expectation of cart movement affect the control of trunk motion at movement onset in cart pushing

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As unexpected sudden unloading of the trunk may cause low-back injury, the objective of the present study was to investigate whether handle height and the expectation of cart movement in pushing affect trunk control at movement onset. Eleven healthy male participants pushed a 200-kg cart with handles at shoulder and hip heights. The cart would suddenly move when externally released (externally triggered condition) or when static friction was overcome (self-initiated condition). Before self-initiated cart movement, trunk stiffness and muscle activity were significantly higher than before an externally triggered onset at comparable pushing force. Lower muscle activity and trunk stiffness at shoulder height compared with the hip height before the onset resulted in higher trunk inclination after the onset. In conclusion, higher preparatory activation of trunk muscles serves to increase trunk stiffness in anticipation of cart movement and may reduce the impact of the perturbation associated with the onset of cart movement.

Statement of Relevance: Sudden cart movement in pushing causes an unexpected unloading perturbation to the trunk. This perturbation was shown to cause uncontrolled trunk movement, which may explain how pushing tasks can be associated with low-back injury. Effects of handle height and awareness of the subjects of the possible cart movement suggest directions for prevention.

Keywords: spine; occupational biomechanics; low-back pain; manual material handling

1. Introduction

Unexpected sudden loading and unloading of the trunk have been considered as challenges to trunk muscle control (Toussaint *et al*. 1998, Cholewicki *et al*. 2000, 2005, van der Burg and van Dieën 2001, Moseley *et al*. 2003, Lee *et al*. 2011). Inadequate responses to the perturbation are considered to be a risk factor for low-back injury (Radebold *et al*. 2000, Cholewicki *et al*. 2005).

During pushing tasks at the workplace, sudden loading perturbations may occur when a moving wheeled cart is suddenly blocked (Lee *et al*. 2011). However, also sudden unloading may occur. When a worker starts pushing an object to displace it, but it does not move, the worker will increase the push forces and then suddenly and unexpectedly the object may start to move. The sudden movement of the object and the resulting drop in the contact forces between hands and object at that instant can be considered an external perturbation that is comparable to a sudden release experiment (Cholewicki *et al*. 2000, 2005, Radebold *et al*. 2000, Vera-Garcia *et al*. 2006). During pushing, relatively low joint moments around the lumbar spine are observed (Hoozemans *et al*. 2004). As low lumbar moments coincide with relatively low trunk stiffness (Cholewicki and McGill 1996), the spine may be at risk during pushing in case of unexpected situations in which the trunk is suddenly unloaded (Schibye *et al*. 1997, Hoozemans 2001).Therefore, the overall objective of the present study was to determine whether the transition from static to dynamic friction in pushing causes a perturbation of the trunk and whether previous findings from sudden release experiments generalise to this realistic work task.

The mechanical stability of the trunk depends on appropriate muscle control before the perturbation and on the responses to the perturbation (Cholewicki *et al*. 2000, 2005, McGill *et al*. 2003). In controlled experiments, the muscle responses to sudden loading consist of fast antagonist activation and agonist de-activation (Cholewicki *et al*. 2000). Trunk muscle co-activation (bracing) before the perturbation was, furthermore, shown to reduce the amplitude of trunk displacement in such experiments (Brown *et al*. 2006). In experiments with sudden additional loading, not only co-activation (Vera-Garcia *et al*. 2006) but also

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higher muscle activity associated with a higher force against an initial external load enhanced trunk stability and reduced response amplitudes after the perturbation (Chiang and Potvin 2001, Gardner-Morse and Stokes 2001, Vera-Garcia *et al*. 2007). Similarly, in pushing tasks when the cart was blocked, the trunk was less perturbed in conditions with higher trunk muscle pre-activation, i.e. when pushing at hip height compared with the shoulder height (Lee *et al*. 2011). It is still unclear whether this generalises to a sudden release, but this might suggest that the relatively low activation of trunk muscles when pushing at shoulder height may result in lower robustness against the sudden release perturbation associated with the onset of cart movement and potentially with higher risk of low-back injury compared with pushing at hip height (Lee *et al*. 2011). Therefore, we hypothesised (1.a) that trunk stability is lower before the onset of cart movement when pushing a four-wheeled cart at shoulder height than at hip height, (1.b) that this will lead to larger changes in trunk inclination after the sudden movement onset and (1.c) more pronounced trunk muscle responses.

During pushing, the moment around the lumbar spine is associated with the level and direction of the exerted hand forces (Hoozemans *et al*. 1998). The exerted hand forces during a typical dynamic pushing task in which a four-wheeled cart is displaced can be divided into three phases (van der Beek *et al*. 1999). In the initial phase, the exerted hand force is increased to overcome the static friction between the cart and the surface and, subsequently, to accelerate the cart. In the following sustained phase, a lower hand force maintains the cart at a constant speed. At the end of a pushing task, a pulling force decelerates and stops the cart. The transition from the initial to the sustained phase in pushing is associated with a sharp drop in the contact forces between cart and hands. As mentioned above, this sudden change in force can be considered as an external perturbation, timing of which cannot be predicted. However, for self-initiated pushing, workers are aware that the cart will at some instant start moving. This may be comparable with a warning preceding sudden loading, which has been shown to cause an increase in trunk muscle activation before the perturbation, resulting in a decrease in trunk displacement directly after the perturbation (Lavender *et al*. 1993, Mawston *et al*. 2007). Therefore, the second hypothesis in the present study is (2.a) that more co-activation of trunk muscles occurs before a self-initiated onset of cart movement than following an externally triggered onset of movement and (2.b) that the change in trunk posture after the onset of movement is smaller in the self-initiated condition.

2. Methods

2.1. Participants

Eleven healthy male volunteers [age 29.5 (SD 5.0) years, height 1.86 (SD 0.06) m and weight 79.7 (SD 8.4) kg] participated in the experiment after signing an informed consent. Participants reported no history of low-back pain or other musculoskeletal disorders within the past 12 months. The ethics committee of the Faculty of Human Movement Sciences approved the experiment.

2.2. Experimental design and procedure

Before the start of the experimental pushing activities, participants performed a series of contractions meant to elicit the maximum isometric voluntary contractions (MVCs) of each of the trunk muscles studied (McGill 1991). Then, participants familiarised themselves with the task of pushing a four-wheeled cart for about 5 min. The cart (height 1.6 m, depth 0.8 m and width 0.64 m) weighed 200 kg and had hard rubber wheels (0.028 m wide and diameter 0.124 m). The two wheels nearest to the participant could swivel. Force transducers were attached to the two handles, at the participant's shoulder height (acromion angle) or hip height (upper border of greater trochanter).

Two remote-controlled calliper breaks attached to the front wheels could be used to prevent the cart from moving (Figure 1).

Participants had to perform self-initiated pushing tasks in which they had to push the cart from standstill over a distance of about 5 m at normal walking velocity at hip and shoulder height (self-initiated condition). Furthermore, participants had to push the cart although the brakes on the front wheels were operative, also at hip and shoulder height. After several reference trials in which the brakes were not released, in the following trial, the brakes were suddenly and unexpectedly released (externally triggered condition). A random number of (4–6) reference trials was performed to avoid the participants becoming aware of the externally triggered condition and to create an unexpected perturbation. The sequence of the tasks, i.e. two pushing conditions (self-initiated and externally triggered) and two pushing heights (shoulder and hip height), was randomised.

2.3. Data acquisition

Exerted hand forces and kinematic data of light-emitting diode (LED) cluster markers on the upper body segments were collected by three-dimensional (3D) force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) and an Optotrak

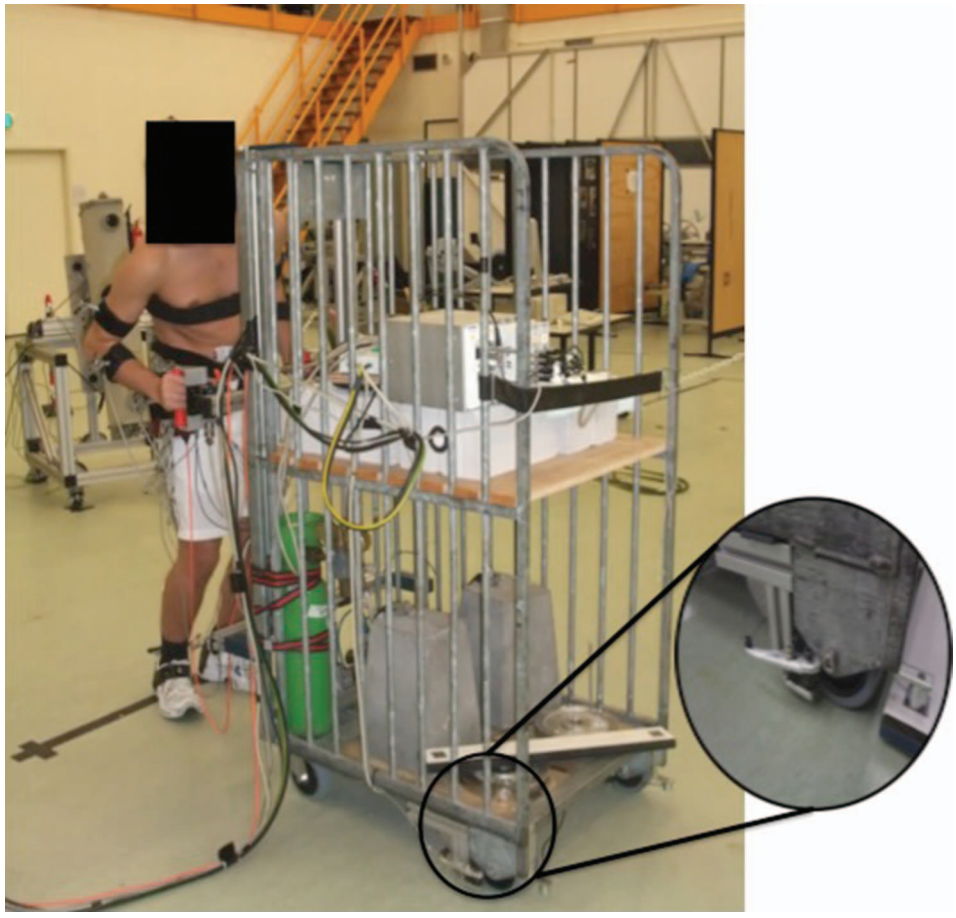

Figure 1. The experimental setup, showing the four-wheeled cart instrumented with two calliper breaks on the front wheels.

system (Northern Digital, Waterloo, ON, Canada), respectively. Force data were stored at 1000 samples/s and then reduced to 50 samples/s using a running average. Clusters of three LED markers were attached to a 50-mm equilateral triangle metal plate on a double hinge joint. Clusters were placed on the pelvis, thorax, bilateral upper arms and forearms, and additional markers were placed at the handles of the cart. Marker positions were recorded at 50 samples/s. The internal moment at the L5–S1 intervertebral disc was estimated from the reaction forces at the hands and the anthropometry and kinematics of upper body segments, using an inverse dynamic model (Kingma *et al*. 1996). Markers on the handles were used to calculate the position of the cart and the onset of cart movement.

Electromyograms (EMGs) were recorded by using disposable Ag/AgCl surface electrodes (Blue Sensor; lead-off area 1.0 cm^2, inter-electrode distance 2.5 cm). After abrasion and cleaning with alcohol, electrodes were bilaterally attached over internal oblique [OI: 3 cm medial to the anterior superior iliac spine (ASIS)], external oblique (OE: halfway the axial line between the 10th rib and the ASIS), rectus abdominis (RA: 3 cm lateral to the umbilicus), multifidus (MU: 2 cm lateral to L4–L5), longissimus thoracis pars lumborum (LL: 3 cm lateral to L3), iliocostalis lumborum (IL: 6 cm lateral to L2), iliocostalis thoracis (IT: 6 cm lateral to T11) and longissimus thoracis pars thoracis (LT: 3 cm lateral to T10). EMG signals were band-pass filtered (10–400 Hz), amplified (20 times, Porti-17^{TM}, TMS, Enschede, The Netherlands; input impedance $>10^{12}$ Ω, common mode rejection ratio >90 dB) and stored on disk (sample rate 1000 samples/s; 22 bits). Electrocardiography (ECG) contamination was identified by means of independent component analysis and removed from the signals (Lee *et al*. 2010). Subsequently, EMG signals were high-pass filtered at 20 Hz and band-stop filtered at 50 Hz and, finally, full-wave rectified and low-pass filtered at 2 Hz (2nd order Butterworth). The signals of the MVC trials were processed using the same steps and the maximal values were used to normalise the EMG signals.

2.3.1. Data analyses for the effects of handle height in the externally triggered condition (Hypothesis 1)

The effects of handle height on amplitudes of trunk muscle EMGs, trunk internal moment and trunk inclination were determined. After normalisation to the MVC values, EMG amplitudes of bilateral RA, OE and OI were averaged to represent abdominal muscle activity, and bilateral MU, LL, IL, IT and LT EMG amplitudes were averaged to represent back muscle activity. The average values of the internal, sagittal plane moment, trunk inclination in the sagittal plane, abdominal muscle and back muscle activities of the second before cart movement were considered as the baseline values.

To analyse trunk stability before the cart movement, an EMG-driven model was used (van Dieën 1997, van Dieën and Kingma 2005, Staudenmann *et al.* 2007). The EMG-driven model consisted of 164 muscle slips crossing the L5–S1 joint and has been described in more detail previously. The 16 normalised EMG signals were assigned to each of the 164 muscle slips in the model. For each trial, a best fit between net moments from the dynamic 3D linked segment model and muscle moments was obtained by optimising the maximum tension in the muscles. Subsequently, muscle forces were estimated as the outcome of the optimal muscle maximum tension, normalised EMG amplitude and correction factors for the instantaneous muscle length and contraction velocity (Kingma *et al.* 2010). The dependent variable was the q_{crit}, calculated on the basis of the joint stability index for the sagittal plane (S_y) proposed by Potvin and Brown (2005):

$$q_{crit} = \frac{S_y + \mathrm{Ph} - \sum_{m=1}^{N} \left[F(A_x B_x + A_z B_z - r_y^2)/l \right]_m}{\sum_{m=1}^{N} \left[F r_y^2 / L \right]_m} \quad (1)$$

In this equation, the index m refers to muscle and N represents the total number of trunk muscles in the model. The muscle force (F), the origin and insertion coordinates in the sagittal plane with respect to joint of interest at L5–S1 (A_x, A_y, A_z; B_x, B_y, B_z), the initial distance (l) from (A_x, A_y, A_z) to (B_x, B_y, B_z), the functional moment arm of the muscle about the y-axis (r_y), the total muscle length from origin to insertion (L) were obtained from the EMG-driven model. The potential energy of the body mass above L5–S1 (Ph) was estimated from the inverse dynamics model.

The q_{crit} was the critical value of q, which is the proportionality constant relating muscle force to stiffness (Potvin and Brown 2005). The q_{crit} is the value of q at which the trunk would be critically stable in the given configuration (Stokes and Gardner-Morse 2003). The spine is thus stable when q is greater than q_{crit}. Given the uncertainty about the actual value of q, q_{crit} was used to represent the level of trunk stability with the lower values interpreted as a larger margin of stability.

To determine changes after the onset of movement, the peak values of internal sagittal plane moments, trunk inclination and abdominal and back muscle activities observed in the first second after movement of the cart were determined. Subsequently, the differences between the peak values after cart movement and the baseline values were considered as the response amplitudes.

The effects of handle height on timing of muscle reflex responses was determined by EMG onset and offset times and evaluated in the externally triggered condition only, because of the constant baseline activity (static component) before perturbations in this condition. Bilateral MU, LL, IL, IT and LT muscles were co-activated as antagonists in static pushing, and the raw EMG data were used to detect the onset time after the onset of cart movement. In addition, the raw EMG data of agonists (bilateral RA, OE and OI) were used to detect the offset time. The onset and offset times were estimated with an approximate generalised likelihood ratio algorithm (Staude and Wolf 1999). Corrections of onset and offset times were made as needed on the basis of visual inspection by a single observer.

2.3.2. Data analyses for the effects of expectation of cart movement (Hypothesis 2)

To compare the externally triggered and the self-initiated condition, the instant of cart movement was used to synchronise the two conditions. Bilateral exerted forces in the horizontal direction at both hands were summed. The force at the instant of cart movement was determined. The rate of reduction of the force after cart movement was defined as the ratio of the difference between the hand force at the instant of cart movement and the lowest force after that instant and the time period between these two points. The hand force at the instant of cart movement and the rate of force reduction were used to evaluate the similarity of the externally triggered and the self-initiated conditions.

The average trunk inclination, abdominal muscle and back muscle activities over 100 ms preceding cart movement were considered as the baseline values, reflecting the preparatory state of the participant. Also, trunk stability before cart movement, indicated by the q_{crit}, was compared between conditions. To compare trunk muscle responses and changes in trunk inclination, the same analysis was used as described for Hypothesis 1.

2.4. Statistics

As most of the data appeared to be skewed to the right, data were logarithmically transformed. For all, paired-samples t tests were used, with p values <0.05 were considered as statistically significant.

2.4.1. Statistical analyses for Hypothesis 1

The baseline values of internal moment, trunk inclination, abdominal and back muscle activities and q_{crit} were compared between pushing at shoulder height and hip height. In addition, changes in internal moment, inclination and muscle activity after movement onset were compared. Finally, the EMG onset times of bilateral MU, LL, IL, IT and LT and the EMG offset times of bilateral RA, OE and OI were compared between pushing at shoulder height and hip height.

2.4.2. Statistical analyses for Hypothesis 2

The hand force at the instant of cart movement and the rate of force reduction were compared between the externally triggered and the self-initiated conditions to test the difference between the external perturbation conditions. To compare the preparatory states of the participants between the externally triggered and the self-initiated condition, we tested for differences in the values of q_{crit}, trunk inclination, and abdominal and back muscle activities. Finally, to compare reactions to the perturbations, muscle responses and changes in trunk inclination were tested for the differences between conditions.

3. Results

3.1. Effects of handle height in the externally triggered condition

A typical example of the data of one participant is shown in Figure 2. The data are presented for the externally triggered condition at shoulder (left) and hip height (right). The vertical lines represent the instant of cart movement after the sudden release of the brakes, and the data are presented for 200 ms before this instant and 1 s after this instant. When pushing at shoulder height, a decrease in internal moment (which is a decrease in flexor moment followed by an increase in extensor moment) coincided with an increase in trunk inclination after the cart movement. For pushing at hip height, the internal moment and trunk inclination were nearly constant.

At the group level, the average internal moment (5.62 SD 20.97 N m at shoulder height and −33.29 SD 21.57 N m at hip height) and trunk inclination (14.09 SD 5.92° at shoulder height and 26.85 SD 13.89° at hip height) during 1 s before the cart movement were significantly affected by handle height ($t(10) = 3.987$, $p = 0.003$ and $t(10) = -2.263$, $p = 0.047$). The abdominal EMG amplitudes before the start of the cart movement were around 3% MVC and were not significantly different between handle heights (Figure 3 and Table 1). For back muscle activity, as expected, the EMG amplitude before the perturbation was significantly higher at hip height (8.42 SD 4.32% MVC) than at shoulder height (2.76 SD 2.30% MVC). Furthermore, the q_{crit} was 11.07 (SD 3.70) at shoulder height and 5.90 (SD 1.54) at hip height and was significantly affected by handle height ($t(10) = 4.345$, $p = 0.001$).

As expected, back muscle activity did increase in response to the perturbation. The EMG onset times averaged over all back muscles, and participants were 198.15 (SD 134.16) ms at shoulder height and 224.51 (SD 178.29) ms at hip height (Figure 4). The back muscle activity reached 8.50 (SD 5.12)% and 13.36 (SD 7.80)% MVCs averaged across participants when pushing at shoulder height and hip height. Abdominal muscle activity first slightly increased following the perturbation at both heights and decreased later, for which the offset times were determined. The EMG offset times averaged over all abdominal muscles (agonists), and all participants were not significantly different between heights with 457.53 (SD 96.96) ms at shoulder height and 459.36 (SD 131.15) ms at hip height (Figure 4). Summarising, the EMG onset times and offset times were around 200 ms and 500 ms, and changes in flexor and extensor muscle activities were at approximately 1% and 5% MVCs, in contrast with our hypothesis, not significantly different between shoulder height and hip height (Table 1). In line with our hypothesis, however, the maximum changes of internal moment and trunk inclination after the cart movement were significantly larger at shoulder height (−23.10 SD 12.91 N m and 4.36 SD 2.48°) than at hip height (−11.58 SD 6.86 N m and 1.84 SD 1.85°; Figure 3 and Table 1).

3.2. Effects of expectation of cart movement

Given the finding above that pushing at shoulder height appears more sensitive to the perturbation caused by the onset of movement, the analysis in this part was restricted to the tasks performed at shoulder height. Typical examples of the contact forces (sum of force exerted in the horizontal direction with both hands) of one participant for pushing the cart in the externally triggered and self-initiated pushing conditions are shown in Figure 5. The vertical solid line is the instant that the cart started to move. As

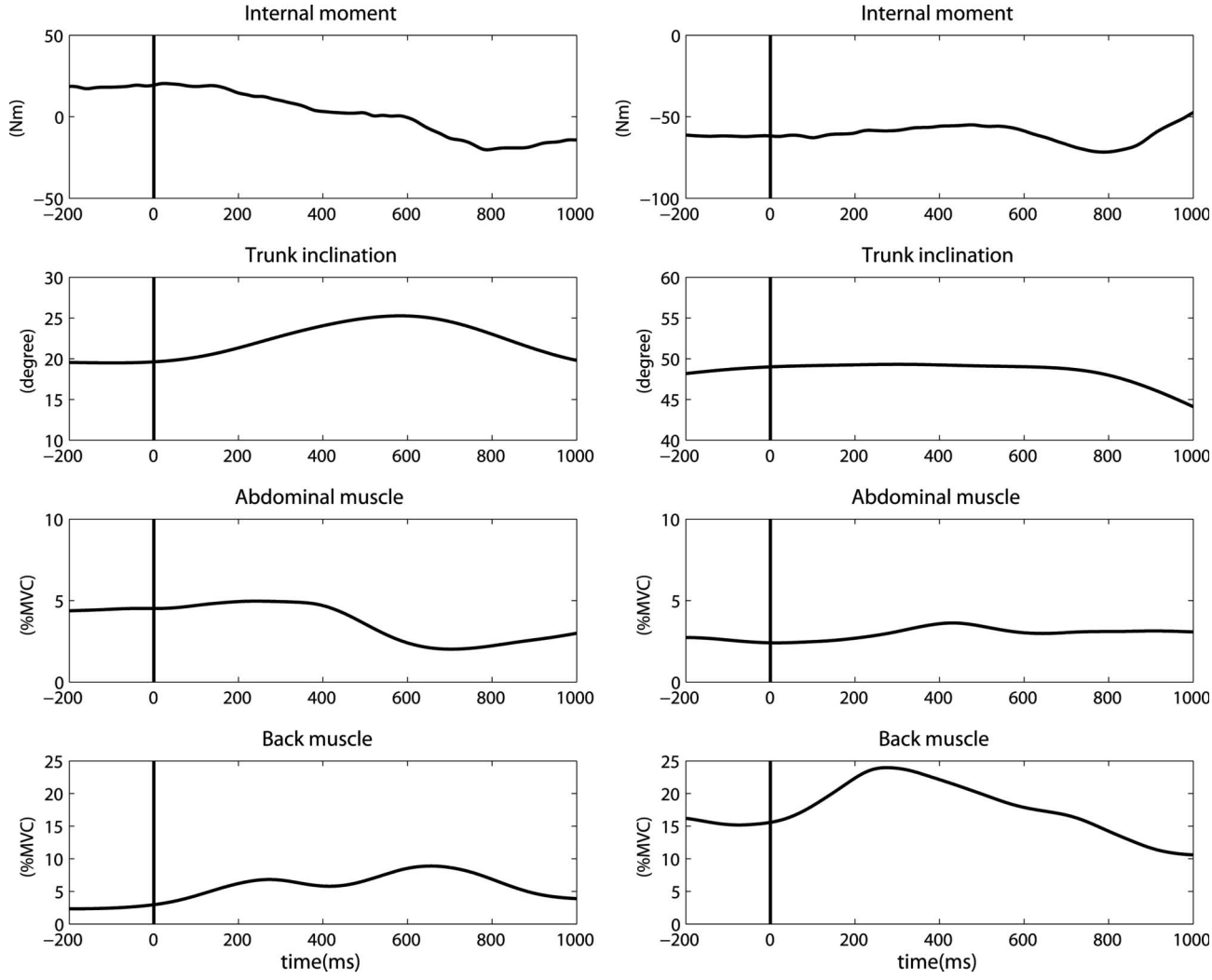

Figure 2. Typical example of a participant pushing a 200 kg cart in the externally triggered condition at shoulder height and hip height. The vertical lines represent the onset time of cart movement. Positive and negative internal moments represent flexor and extensor moments, respectively. Positive trunk inclination represents flexion. The left and right panels represent pushing at shoulder and hip height, respectively.

expected, similar patterns were observed in both conditions after this instant. This similarity is confirmed in the analyses at the group level. The average peak hand forces were 180.25 (SD 33.99) N in the externally triggered condition and 181.18 (SD 25.15) N in the self-initiated pushing condition ($t(10) = -0.220$, $p = 0.831$). Furthermore, pushing condition did not affect the rate of force decrease (decrease in exerted hand force after cart movement; $t(10) = 1.160$, $p = 0.273$).

To compare trunk stability between the two conditions, the q_{crit} before cart movement was evaluated. The value of q_{crit} in the self-initiated condition (7.40 SD 3.52) was significantly lower than in the externally triggered condition (11.07 SD 3.70; Table 2). This difference can be explained by the EMG amplitudes of abdominal and back muscles before the cart movement, which is shown in Figure 6. Pushing condition significantly affected trunk abdominal and back muscle activities, which were higher in the self-initiated condition (4.34 SD 1.86% MVC and 4.66 SD 3.13% MVC) than in the externally triggered condition (3.23 SD 1.17% MVC and 2.76 SD 2.30% MVC). After cart movement, the changes in trunk muscle activity were significantly larger in the externally triggered condition than in the self-initiated condition, whereas the peak values of abdominal and back muscle activities were not significantly different between conditions. The change in trunk inclination after the cart movement was somewhat larger in the externally triggered condition, but this was not significant (Figure 6 and Table 2).

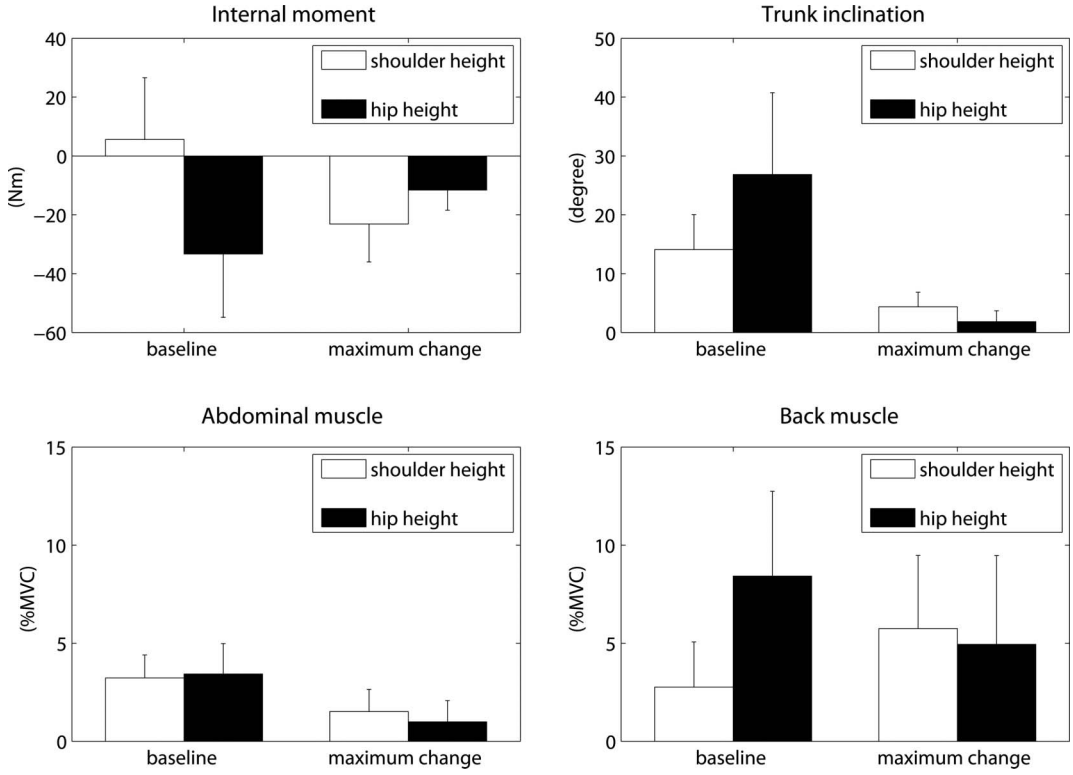

Figure 3. Means and standard deviations (error bars) of internal moment, trunk inclination and EMG amplitudes at group level. The left and right panels represent baseline and maximum change, respectively. Positive internal moments represent the flexor moments; positive trunk inclination represents flexion. The white and black boxes represent pushing at shoulder and hip height, respectively.

4. Discussion

The objectives of the present study were to investigate whether the onset of cart movement in pushing, i.e. the transition from static to dynamic friction, causes a perturbation of the trunk and whether previous findings from sudden release experiments generalise to this realistic work task. More specifically, we aimed to determine how handle height affects trunk muscle activity and changes in trunk inclination in response to sudden unloading and how trunk inclination and trunk muscle activity are affected by the expectation of cart movement. As hypothesised, before the cart movement, lower q_{crit} and higher trunk extensor muscle activity were observed in pushing at hip height compared with pushing at shoulder height. Furthermore, after the onset movement of cart movement, smaller changes in trunk inclination, internal moments and back muscle activity were observed at hip height than at shoulder height. In contrast with our hypothesis, however, trunk muscle onset and offset times were not affected by handle height. The pattern and level of the contact forces between hand and cart around the onset of cart movement were similar for the externally triggered and the self-initiated conditions. In the self-initiated condition, lower q_{crit} coinciding with higher trunk muscle activity was observed before the cart movement. This suggests a higher level of trunk stiffness associated with the expectation of the cart movement. The data did, however, not confirm that this prevented an increase in trunk inclination after the cart movement. Trunk muscle activity reached similar levels of activity after the cart movement, suggesting that larger changes occurred in the externally triggered condition.

4.1. Effects of handle height in the externally triggered condition

The sudden decrease in contact forces between the hands and the cart after the brakes of the cart were released, and the cart started to move, caused a drop in the external extension moment on the trunk, which required muscular effort to restore trunk equilibrium. The extensor muscles, antagonists during static pushing, were activated, and the flexor muscles,

Table 1. Results of the paired-samples *t* test to determine the differences between shoulder height and hip height.

Paired-samples *t* test (shoulder height vs. hip height)		
	t(10)	*p*
q_{crit}	4.345	**0.001**

Paired-samples *t* test (shoulder height vs. hip height)				
	Baseline		Maximum change	
	t(10)	*p*	*t*(10)	*p*
Internal moment	3.987	**0.003**	−2.263	**0.047**
Trunk inclination	−3.213	**0.009**	3.240	**0.009**
Abdominal muscle activity	−0.336	0.744	1.123	0.288
Back muscle activity	−4.661	**0.001**	1.113	0.292

Paired-samples *t* test (shoulder height vs. hip height)					
		Left side		Right side	
		t(10)	*p*	*t*(10)	*p*
EMG onset time	MU	−1.470	0.172	0.426	0.679
	LL	−1.871	0.091	−1.675	0.131
	IL	0.283	0.783	−0.080	0.938
	IT	1.329	0.213	−0.161	0.875
	LT	0.268	0.794	−0.926	0.376
EMG offset time	RA	−0.408	0.692	1.217	0.251
	OI	0.438	0.671	−1.216	0.252
	OE	−1.399	0.192	1.028	0.328

Note: Significant *p* values are indicated in bold. Negative *t* values indicate higher values in pushing at hip height, except for the internal moment, where, because of the negative values of the change of moment, negative *t* values indicate higher values in pushing at shoulder height.

agonists during static pushing, were switched off as has been shown in more controlled sudden release experiments in which the trunk was loaded and unloaded directly (Cholewicki *et al.* 2000, 2005). The onset times of the extensor muscles and the offset times of the flexor muscles were around 200 ms and 500 ms, respectively, much later than what was observed in controlled suddenly unloading experiments (Cholewicki *et al.* 2000, 2005, Radebold *et al.* 2000). This may be because of the differences in the kind of imposed perturbation. In the present study, the perturbation was applied to the hands, whereas, in other studies, the perturbations were imposed directly to the trunk. Because fast responses (<50 ms delay) of trunk muscles to perturbations applied to the arm were observed in a previous study (Hodges *et al.* 2001), most likely, the slower responses can be explained by the slower drop in the external moment in the present realistic task than in the previous experiments. The onset and offset times varied widely (Figure 4), but responses occurred before the minimum contact force occurred.

In contrast with our hypothesis, trunk muscles were neither more active after the release when pushing at shoulder height compared with the hip height nor were they activated faster. Compared with pushing at hip height, the baseline level of back muscle activity was lower and the q_{crit} before the perturbation was higher at shoulder height. This indicates a lower level of trunk stiffness when pushing at shoulder height compared with pushing at hip height, because of the lower pre-activation of the back muscles when pushing at shoulder height. In the absence of quick muscle responses compensating for the lower stability of the trunk, ensuing motions may exceed safe boundaries (Cholewicki *et al.* 2000). Indeed, larger changes in trunk inclination after sudden unloading were observed at shoulder height compared with the hip height. The increase in trunk inclination coincided with a decrease in internal moment, i.e. an increase in extensor moment. This suggests that an involuntary trunk motion occurred. Similar results, though in an opposite direction, were observed when a cart was blocked during pushing (Lee *et al.* 2011). Taken together, these findings suggest an increase in potential injury risk because of the unexpected changes in cart movement when pushing at shoulder height.

The constant pushing force before the sudden release of the brakes suggests that participants did not

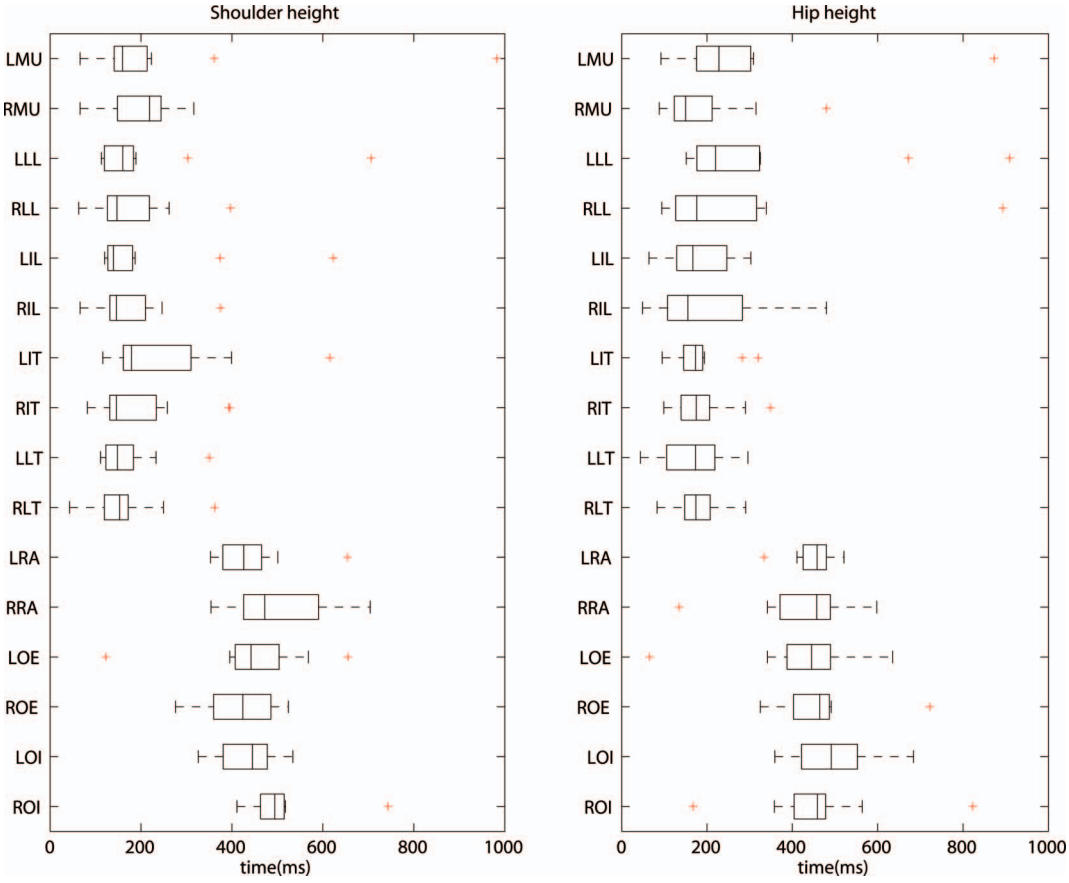

Figure 4. EMG onset times of antagonists and offset time of agonists. In the present study, bilateral back muscles (LMU, RMU, LLL, RLL, LIL, RIL, LIT, RIT, LLT and RLT) are antagonists and bilateral abdominal muscles (LRA, RRA, LOE, ROE, LOI and ROI) are agonists. The left and right portions represent pushing at shoulder and hip height, respectively.

anticipate this external perturbation. The unexpectedness of the perturbation was also confirmed by the fact that the internal moments, trunk inclination and EMG amplitude were nearly constant before the perturbation and that all parameters changed only after the perturbation.

The q_{crit} was calculated on the basis of the parameters obtained from the EMG-driven model. The model was used to fit the relationship between trunk muscle activity and internal low-back moments estimated using the dynamic 3D linked segment model. The internal moments averaged over both heights were estimated at 29.63 N m by the EMG-driven model and 29.84 N m by the dynamic 3D linked segment model. The root-mean-square (RMS) error between these moment estimates ranged over participants from 1.14 to 13.87 N m. Hence, the estimated q_{crit} does suffer from estimation errors. The RMS errors, however, were not different between conditions, and, moreover, conclusions based on q_{crit} were in accordance with the EMG amplitudes.

4.2. *Effects of expectation of cart movement when pushing at shoulder height*

As a potential risk of low-back injury was detected for sudden unloading when pushing at shoulder height, it is relevant to investigate whether responses are different when cart movement during this task is self-initiated. Similar patterns and levels of contact forces were observed in the externally triggered and self-initiated conditions around the onset of cart movement. This suggests that the externally induced sudden unloading in the present study is comparable to the initial phase of pushing tasks during which the pushing force exceeds the static fiction of the cart.

However, before the onset of cart movement, higher abdominal and back muscle activities were found in the self-initiated condition compared with the externally triggered condition. These results indicate a higher level of trunk muscle co-contraction that increases the trunk stiffness (lower q_{crit}). Participants knew that the cart was not locked in the self-initiated condition, which apparently triggered such

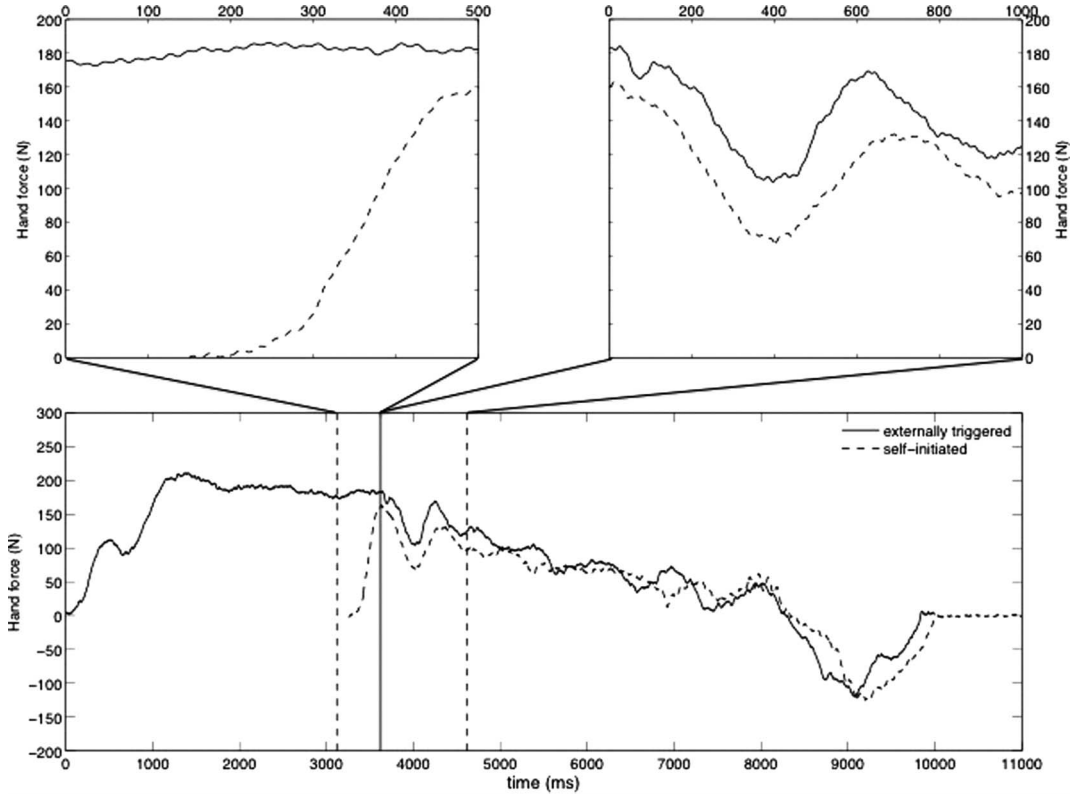

Figure 5. Typical example of a participant pushing a 200 kg cart at shoulder height in the externally triggered (solid lines) and self-initiated (dash lines) conditions. The vertical solid line represents the onset of cart movement. The left upper panel is a zoomed in image of the period (500 ms) from the left vertical dashed line to the vertical solid line. The right upper panel represents the period (1000 ms) from the vertical solid line to the right vertical dash line.

Table 2. Results of the paired-samples t test to determine the differences between self-initiated and externally triggered conditions.

Paired-samples t test (self-initiated vs. externally triggered)		
	$t(10)$	p
q_{crit}	−3.949	**0.003**

Paired-samples t test (self-initiated vs. externally triggered)						
	Baseline		Peak		Maximum change	
	$t(10)$	p	$t(10)$	p	$t(10)$	p
Abdominal muscle activity	2.578	**0.028**	−1.015	0.334	−3.711	**0.004**
Back muscle activity	3.759	**0.004**	−1.048	0.319	−3.161	**0.010**
Trunk inclination	−0.124	0.904	−1.080	0.306	−1.550	0.152

Note: Significant p values are indicated in bold.
Negative t values indicate higher values in the externally triggered condition.

preparatory co-contraction, similar to that in sudden loading experiments in which the participant is warned for an impending perturbation (Lavender *et al.* 1993, Lavender and Marras 1995, Mawston *et al.* 2007). Because of this preparatory trunk co-contraction, a low risk for low-back injuries would be expected after sudden, yet anticipated, unloading during pushing. Indeed after the onset of cart movement, the peak trunk inclination was smaller in the self-initiated than the externally triggered condition,

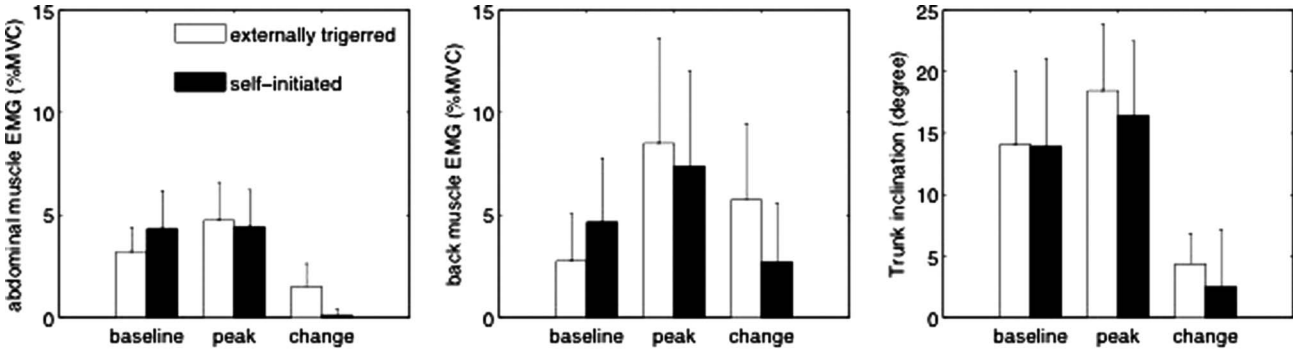

Figure 6. Means and standard deviations (error bars) of abdominal and back muscle EMG amplitudes and trunk inclination when pushing at shoulder height. The white and black boxes represent pushing in externally triggered and self-initiated conditions, respectively. The baseline amplitudes, peak values and changes after perturbation of abdominal muscle, back muscle and trunk inclination are shown from the left to right.

though not so significant. Larger changes in abdominal and back muscle activities occurred in the externally triggered condition implying that a larger response of the extensors may have prevented a large change in trunk inclination. The present study involved young healthy male, but inexperienced, participants only. Generalisation to other populations, such as experienced manual material handlers or females, should, therefore, be considered with care.

5. Conclusion

In conclusion, when cart movement is unanticipated, pushing at shoulder height may impose a higher risk of low-back injury than pushing at hip height because of the lower trunk stiffness and larger involuntary trunk motion after the onset of cart movement. In the initial phase of self-initiated cart pushing, preparatory co-contraction of trunk muscles served to increase trunk stiffness in anticipation of cart movement. The preparatory co-contraction of trunk muscles in this situation may reduce the risk of low-back injury.

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