Effects of sudden cart movement on the trunk in different phases of cart pushing

Pushing is a common task of manual material handling activities in many workplaces and considered as a risk factor of low-back pain. When performing pushing tasks, sudden and unexpected changes in exerted hand forces may induce the mechanical perturbation to the trunk. Additionally, handle height is one of the ergonomic factors as well as expectation of the impending perturbations, which may affect trunk posture and trunk muscle activity when the perturbations occur.
Therefore, we aimed to evaluate the factors of handle height and expectations on the trunk during an initial phase, a sustained phase and an end phase in pushing tasks. When pushing at hip height or expected the changes in exerted forces, increases in trunk muscle activity and decreases in trunk inclination after the perturbations in three phases were observed. We recommend reducing the possibility of unpredictable perturbations to decrease the risk of low back injury.

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In daily life, we are continuously exposed to mechanical perturbations of trunk equilibrium, particularly when performing manual material handling devices. Pushing and pulling are common manual materials handling activities and have replaced lifting and carrying in many workplaces to prevent the development of low-back pain (Schibye e.a., 1997). However, pushing and pulling activities can also contribute to the risk of low-back pain (Damkot e.a., 1984; Harber e.a., 1987; Hoozemans, 2001; Plouvier e.a., 2008).
Taking the task of pushing a wheeled object, such as a four-wheeled cart, as an example the pattern of the horizontal hand forces in the forward/backward direction can typically be divided into three phases (figure 1): an initial phase, a sustained phase and an end phase (van der Beek e.a., 1999). In the initial phase, the (pushing) hand force is increased to reach a peak value to overcome the static friction between the cart and the floor and subsequently to accelerate the cart. In the following sustained phase, a smaller hand force maintains the cart at a constant speed. At the end of the task, a hand force in the opposite direction (pulling) decelerates and stops the moving cart.

Sudden changes in exerted hand forces during the pushing task, for instance by sudden, and sometimes unexpected, cart movement, cause loading and unloading of the trunk. Therefore, sudden and unexpected changes in exerted hand forces during pushing can be considered as mechanical

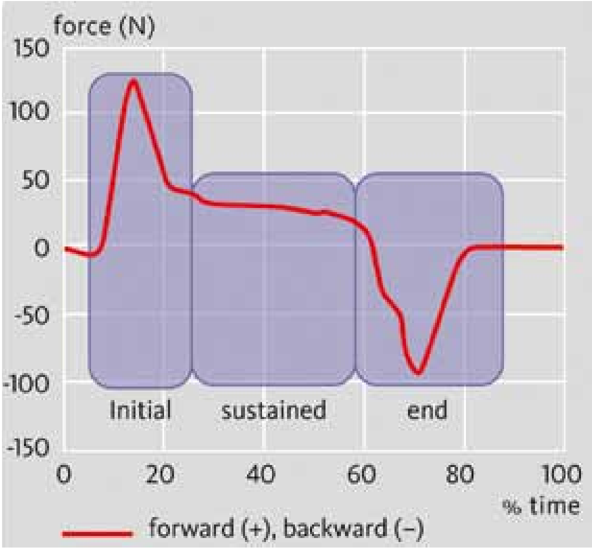

Figure 1. A schematic representation of exerted hand forces in the forward/backward direction in the initial, sustained and end phases of pushing a four-wheeled cart (based on Van der Beek e.a., 1991)

perturbations of the trunk, which challenge trunk stability (Cholewicki and McGill, 1996). To control trunk posture, trunk muscles either need to create sufficient stiffness of the trunk prior to the perturbation by simultaneous activity of muscles on both sides of the joint (co-contraction) or need to respond quickly to counteract the perturbation. Delayed muscle activation or inappropriate muscle activation may increase the risk of low back injury (Cholewicki e.a., 2005).

When performing pushing tasks, the exerted hand forces are directed away from the body, while the trunk is inclined (figure 2). The opposite directed moments at the low back accounts for the overall low net moment at the low back (De Looze e.a., 2000; Hoozemans e.a., 2004; Hoozemans e.a., 2007) This will coincide with a relatively low trunk muscle activity, which is associated with low trunk stiffness and low trunk stability. Consequently, it may thus enhance the negative effects when mechanical perturbations occur (Cholewicki and McGill, 1996; Cholewicki e.a., 2005; Schibye e.a., 1997). Pushing carts has therefore been suggested to impose a challenge for trunk muscle control as this system with a relatively low stiffness may have to deal with perturbations induced by a moving cart with a high speed.

In pushing tasks, handle height is one of the ergonomic factors, which influences working demands of pushing tasks since it determines trunk posture and affects trunk muscle activity. When pushing at low handle heights, for instance hip height, trunk inclination is larger and therefore trunk muscle activity is higher, which may reduce the impact of perturbations because higher trunk muscle activity is associated with higher trunk stiffness, which stabilizes the trunk. An additional factor that influences work demands is expectation of an impending perturbation. Expecting the perturbation may lead to early initiation of trunk muscle activity, which may also reduce the impact of the perturbations. Therefore, we aimed to evaluate the factors of handle height and expectations on the trunk when sudden changes in cart movement.

Experimental settings

Three studies were executed to focus on trunk moment perturbations in different phases of pushing tasks. Mechanical perturbations are induced due to the fact that changes in the movements of the cart, for examples, initiating the cart moving forward in the initial phase or bumping into an obstacle in the end phase when performing pushing tasks in real life. In these cases, the forces exerted by both hands are generally symmetric and thus the main effect on trunk moments will occur in the sagittal plane. In the sustained phase, i.e. pushing on the uneven surface, the variation in the horizontal component of the hand force caused by walking affects trunk moments in the transverse plane.

Subjects in the three studies were healthy male volunteers without professional pushing experience without history of low-back pain or other musculoskeletal disorders within the past 12 months. They were instructed to push a 1.6m height, 0.8m depth and 0.64 m width four-wheeled cart with 0.028 m width and 0.124 m diameter hard rubber wheels (figure 3). In order to evaluate the handle height

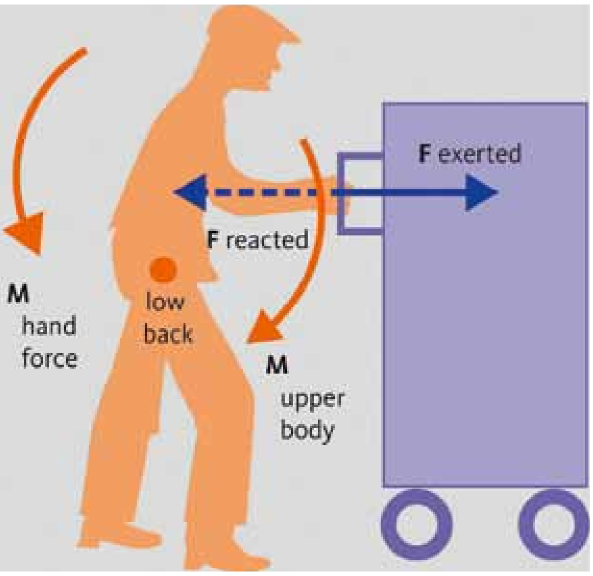

Figure 2. A schematic representation of a worker pushing a cart at shoulder height. The solid arrow represents the exerted hand force (Fexerted) directed away from the body and the dash arrow represents the reaction force (Freaction) in the backward direction at the hands. The counterclockwise circular arrow represents the moment (Mhand force) at the low back due to the reaction force at the hands and the clockwise circular arrow represents the moment (Mupper body) at the low back due to the gravitational force acting on the upper body.

factor, the handles attached on the cart were adjustable for individual subjects. For muscle activity, electromyograms were measured by using disposable Ag/AgCl surface-electrodes (Blue Sensor; lead-off area 1.0 cm^2, inter-electrode distance 2.5 cm). During the experiment, the kinematic data were collected from an Optotrak system (Northern Digital, Waterloo ON, Canada) and calculated trunk inclination by using a 3D inverse dynamics model (Kingma e.a., 1996). Furthermore, the upright posture was defined as zero degree of trunk inclination. Exerted forces at the hands were collected by 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA). The trunk 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 e.a., 1996), which was used to reflect changes in mechanical perturbations in different pushing phases.

Summary of studies

Study I: The initial phase

In the initial phase of pushing, the onset of cart movement during the transition from static to dynamic friction when reaching the maximum horizontal hand forces can be associated with a sudden unloading perturbation. In a laboratory experiment, eleven subjects (age 29.5 (SD 5.0) years, height 1.86 (SD 0.06) m and weight 79.7 (SD 8.4) kg) were asked to push the four-wheeled cart at shoulder height and hip height from standstill *with* expectation of cart movement (self-initiated) and *without* expectation of cart movement (externally triggered by releasing a brake). Compared to pushing at hip height, pushing at shoulder height was associated with lower muscle activity associated with low trunk stiffness before onset of cart movement, which resulted in a larger change in trunk inclination after onset. Trunk stiffness and muscle activity were significantly higher before cart movement in a self-initiated start than before cart movement in an externally triggered start at a comparable pushing force. When pushing at hip height and paying attention of cart movements, trunk muscles initiate higher activation, which serves to increase trunk stiffness. This preparatory action may help to reduce the potential injury induced by the impact of the perturbation when the cart suddenly moves in pushing.

Figure 3. The experimental setup, showing the four-wheeled cart

Study II: The sustained phase

When pushing while walking, the trunk moments are expected to vary cyclically and are self-induced and thus the perturbations (changes in the moments) are predictable for workers. The oblique abdominal muscles are the main contributors to trunk twisting moments. We therefore investigated in a laboratory setting whether cyclic pushing forces when pushing a four-wheeled cart while walking are associated with cyclic oblique abdominal muscle activity. In addition, we hypothesized that external and unpredictable perturbations would be counteracted by co-contraction of the oblique abdominal muscles. Eight subjects (age 26.4 (SD 7.8) years, height 1.82 (SD 0.05) m and weight 79.4 (SD 8.8) kg) were instructed to push the cart at two target forces (1) in a static standing position as a reference condition, (2) while walking and (3) during walking while the target forces were externally and randomly perturbed to simulate the effect of non-constant rolling resistance. A tonic level of oblique abdominal muscle co-contraction to control trunk orientation in the transverse plane in pushing while walking was observed. Additional dynamic muscle activity was observed that was associated with the twisting moments associated with walking, which were actively modulated by the pairs of oblique muscles as in normal gait (Dumas e.a., 1991; Kumar e.a., 2003; Ng e.a., 2001). When pushing while the target forces were externally and randomly perturbed, an increased baseline of oblique abdominal muscle activity reflected increased co-contraction of the antagonistic muscle pairs of the oblique abdominal muscles. However, increased co-contraction of oblique abdominal muscles are not successful in preventing increased trunk twisting movements. Pushing on uneven surface induces unpredictable changes in exerted forces, which causes inefficient trunk muscle activity associated with incomplete control of trunk movement.

Study III: The end phase

As mentioned in the initial phase, while the start of pushing a four-wheeled cart might coincide with a sudden trunk *unloading* perturbation, stopping a cart during a pushing task might coincide with a sudden trunk *loading* perturbation. Two types of sudden stops, a sudden self-initiated stop to avoid a collision and a forced stop due to an obstacle blocking the cart, were stimulated in the laboratory. While pushing a four-wheeled cart, subjects were instructed to stop a cart as fast as possible after an auditory cue (self-generated stop), or the wheels of the cart were unexpectedly blocked using an obstacle that was released in front of the cart's wheels (externally generated stop). The initial responses in both stops consisted of trunk flexor and extensor muscle co-contraction. In the self-generated stops, trunk extension coincided with the trunk moment generated by back muscle activity, indicating that voluntary trunk movement occurred. In the externally generated stops, trunk extension was induced by the trunk moment generated by the effect of the forces on the hands. The trunk moment and trunk motion were specifically observed in the opposite directions when pushing at shoulder height. This indicated that involuntary trunk movement occurred. When pushing the cart, unexpectedly bumping into an obstacle at the working place, a loss control of trunk posture may damage the trunk and cause occupational injury on the back.

Conclusion

In conclusion, the present studies showed that changes in exerted hand forces in different phases of pushing tasks might cause perturbations of the trunk, which challenges the control of trunk posture and may impose a risk of low back injury. In cart pushing, externally generated unpredictable perturbations, especially while pushing at shoulder height, induce involuntary trunk motions counteracted by relatively late responses in muscle activity. Prior to expected and self-generated perturbations, anticipatory activity increases trunk stiffness, but does not completely prevent trunk movement.

Practical relevance

Based on the findings of our studies, the impact of perturbations in pushing was attenuated by the increase in trunk inclination associated with pushing at hip height. We do not recommend a change in handle height in the field when performing the pushing tasks. Prolonged pushing at hip height may induce trunk muscles maintaining a high level of muscle activity for a long period, which would negatively affect muscle responses when perturbations occur. Instead, we recommend keeping the working environment clean, free from obstacles, and with clear visual fields or clearly indicated paths to reduce the possibility of unpredictable and externally generated perturbations, to decrease the risk of low back injury.

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