Control of trunk movement:
Perturbations in cart pushing

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Perturbations in cart pushing
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Outline of this thesis

In daily life, we are continuously exposed to mechanical perturbations of trunk equilibrium. A simple example occurs when we move our arm to reach for a cup of coffee, where the arm movement imposes small and predictable reaction forces on the trunk. A bit more challenging are the dynamic forces on the trunk occurring during walking and when manipulating objects while walking. Unpredictable and large perturbations may occur and maintaining trunk stability can become an extremely complicated task. However, examples of such activities, like pushing a shopping cart around the supermarket, are quite common in daily life.

In the first chapter of this thesis, an overview of biomechanical research on pushing tasks is presented. This chapter also contains a brief introduction of trunk stability and effects of perturbations on the trunk. In the second chapter, it was shown that the transition from static to dynamic friction causes a sudden unloading perturbation of the trunk and the effects of handle height and expectation of the impending perturbation were studied. In the third chapter, sudden loading of the trunk induced by self-generated and externally generated stops during pushing of a cart were studied. The findings of these two studies indicate that externally induced sudden loading and unloading perturbations can cause involuntary trunk motions in the sagittal plane. In addition, a more upright trunk posture was associated with lower trunk muscle activity due to which perturbations caused a larger displacement of the trunk.

The hand forces in pushing while walking are asymmetric between left and right hands, causing twisting moments on the trunk. In the fourth chapter, it was shown that the unpredictable variations in hand forces during walking are counteracted by abdominal oblique muscle co-contraction, which increases trunk twisting stiffness. Turning a cart requires even greater asymmetry of hand forces. In the fifth chapter, it was shown that trunk abdominal rotators are cocontracted in anticipation of making a turn when pushing. This study furthermore showed that when there is insufficient time to prepare a turn, a fast trunk rotation is caused by the interaction with the cart.

In the sixth chapter, a general discussion is given and conclusions are drawn with respect to trunk muscle control in response to perturbations during cart pushing. In addition, the differences between perturbations in realistic tasks such as studied here and more artificial perturbations used in most laboratory studies are discussed.
Chapter 1.

General introduction
General Introduction

Background

Over 80% of all industrial manual handling activities consists of pushing and pulling vehicles like four wheeled carts [74] and manual materials handling is generally considered a cause of occupational injuries of the musculoskeletal system, especially the low back [11, 19, 45, 95]. However, the risk of mechanical injuries to the low back due to pushing and pulling appears to be unclear. Although there is discordance in epidemiological studies on the relationship between pushing and pulling and low-back injuries [31, 46, 67, 90,133], exposure to pushing and pulling is associated with disability in people suffering low back injuries [21, 37, 46, 49, 94]. In pushing, the exerted hand forces are directed away from the body, while the trunk is inclined. Consequently, the moments at low back caused by the reaction forces at the hands and the gravitational force at the upper body are often opposite, which accounts for the overall low net moment at the low back. During pulling, these moments are often in the same direction and result in a higher level of lumbar loading as compared to pushing [23, 47, 48]. Still, lumbar moments in pushing and pulling are much smaller than in lifting tasks, which may explain why generally less scientific and ergonomic attention is paid to pushing and pulling and why a clear epidemiological relationship with low-back injury is lacking.

Even so, pushing and pulling have been suggested to impose a problem in terms of trunk muscle control, because objects with high inertia are transported [13]. As mentioned above, the mechanical load is relatively low in pushing and pulling, which thus can be considered a low-demand tasks. When performing such low-demand tasks, the stability of the spine is low due to a low level of muscular activity [15]. It is suggested that a sudden perturbation of the upper body may induce excessive joint movements or inappropriate trunk muscle control because of the sudden need to increasing muscle activity to regain spine stability, which may result in acute low-back injury [15, 17, 109]. Especially pushing tasks in which four-wheeled carts are handled may in this light be high-risk activities as theses are associated with a low level of lumbar load and low level of trunk muscle activity, as previously indicated, while at the same time a relatively heavy load on wheels has to be controlled. An association between sudden perturbations during pushing and low back problems has not been
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reported or investigated in epidemiological studies. This may even be a mission impossible because of methodological difficulties with the registration of such exposures at the workplace. However, a focus on trunk muscle control and trunk stability in response to sudden perturbations in pushing tasks in a laboratory setting might indicate whether such perturbations at the workplace are potentially harmful for the low back. As evidence on the connection between trunk stability and handling the perturbations in terms of trunk muscle control is missing, this thesis will mainly address trunk muscle control in response to perturbations in cart pushing.

Biomechanics in pushing

In biomechanical models, the net moment at the level of the L5S1 intervertebral joint can be estimated from the reaction forces at the hands and the anthropometry and kinematics of upper body segments using a top-down calculation by inverse dynamics [57]. In the inverse dynamics model used head, trunk, pelvis, bilateral forearms with hands and upper arms are considered as rigid segments. The segmentation plane between the trunk and the pelvis is the lumbosacral junction (L5S1). This is the most common site for the intervertebral disc herniation [36, 132], disc degeneration [26,108] and spodyloisthesis [61]. In addition, joint motion as well as joint moments at the other spinal levels can be expected to be highly correlated to those at L5S1. Trunk moments around L5S1 are mainly due to activity of the internal oblique, external oblique, rectus abdominis, multifidus, longissimus thoracis pars lumborum, iliocostalis lumborum, iliocostalis thoracis and longissimus thoracis pars thoracis muscles [116], which were studied with surface electromyography in the present thesis.

In pushing, the direction and magnitude of the exerted hand forces and the posture of the trunk determine the direction and magnitude of the moment at the L5S1 joint. A typical example of hand forces during a dynamic pushing task in which a four-wheeled cage is given in a study by van der Beek et al. [121] (Fig 1-1). When pushing a wheeled object, the typical pattern of the hand forces in forward/backward direction (horizontal component) can be divided into three phases: an initial phase, a sustained phase and an end phase. In the initial phase, the hand force is increased reaching a peak value to overcome the static friction
General Introduction

between the object and the surface and subsequently to accelerate the object. In the following sustained phase, a smaller hand force maintains the object at a constant speed. At the end of a pushing task, a pulling force decelerates and stops the moving object. When pushing in a straight path, the hand force in the sideward (left/right) direction is kept constant around zero throughout the entire task. In addition, for the upward/downward direction, a gradual downward force in the initial phase, a constant downward force in the sustained phase and a gradual decrease back to 0 N in the end phase.

Figure 1-1: A typical example of a three-dimensional force assessment in the initial, sustained and end phases of a pushing task (based on van der Beek et al., [121]).

As mentioned above, the exerted hand forces are a crucial component of the net moment at the L5S1 joint. A simplified relationship between hand force and net moment is shown in a sketch in Figure 1-2. Before guiding through this sketch, the external and internal net moment at L5S1 will be defined first. The
Chapter 1

external moment contains the sum of two parts. One is the reaction force at hands ($F_{\text{reaction}}$, which is equal but opposite to the exerted hand force) times the perpendicular (or shortest) distance from the center of the L5S1 joint (L5S1) to the line of $F_{\text{reaction}}$ action ($M_{\text{external-HF}}$). The other one is the upper body weight ($\text{COM}_\text{UB}$) times the perpendicular distance from L5S1 to the line of action of the gravitational force at $\text{COM}_\text{UB}$ ($M_{\text{external-UBM}}$). When the external moment ($M_{\text{external-total}}$) is not equal to zero, it tends to accelerate the trunk in the direction of the moment with the largest magnitude (either $M_{\text{external-HF}}$ or $M_{\text{external-UBM}}$). In case of a static equilibrium, to counteract the external moment, trunk muscle activity produces an internal moment ($M_{\text{internal}}$), which is equal but opposite to the $M_{\text{external-total}}$.

In Figure 1-2 it is assumed that the exerted pushing force is directed exactly horizontally. Force exertion is in the forward direction, which coincides with a $F_{\text{reaction}}$ in the backward direction, which results in a counterclockwise $M_{\text{external-HF}}$ at the L5S1 joint. In pushing, the trunk is often inclined in which case the upper body weight produces a clockwise-directed moment at the L5S1 joint ($M_{\text{external-UBM}}$). Generally, $M_{\text{external-HF}}$ is expected to be larger than $M_{\text{external-UBM}}$ due to the larger moment arm with respect to L5S1. Particularly when pushing at shoulder height, the moment arm of $\text{COM}_\text{UB}$ with respect to L5S1 is small because of a relatively upright standing posture with a small trunk inclination. The total external moment ($M_{\text{external-total}}$) is the sum of $M_{\text{external-HF}}$ and $M_{\text{external-UBM}}$, which results in a counterclockwise $M_{\text{external-total}}$, which will induce trunk extension. Consequently, trunk flexor activity produces the $M_{\text{internal}}$ in the clockwise direction at the L5S1 joint to maintain trunk posture.
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Figure 1-2: Representation of a subject pushing a cart at shoulder height. The solid arrow represents the reaction force \( F_{\text{reaction}} \) in backward direction at the hands. The dashed arrow represents the gravitational force acting at the upper body center of mass \( \text{COM}_{\text{UB}} \). The circular arrows represent the external and internal moments. \( M_{\text{internal}} = \) internal moment, \( M_{\text{external-UBM}} = \) external moment produced by upper body mass, \( M_{\text{external-HF}} = \) external moment produced by hand force, \( M_{\text{external-total}} = \) total external moment, \( \text{L5S1} = \) center of the L5S1 intervertebral joint.

This sketch (Fig 1-2) only shows the main forces and moments acting with respect to the low back for a pushing situation in the sagittal plane in which hand forces are exerted in a horizontal direction at shoulder height. Handle height has been considered as a crucial ergonomic factor in pushing (and pulling) \([50, 55, 74]\) and influences pushing capability \([78, 112]\). Several studies \([3, 23, 48]\) have shown that handle height affects the vertical component of the exerted force, i.e. force is exerted in the upward direction when pushing at shoulder height and in the downward direction when pushing at hip height. Taking pushing at hip height as an example, the vertical component of the reaction force in the upward direction results in a counterclockwise trunk moment at the L5S1 joint. Compared to pushing at shoulder height, for pushing at hip height the increase in trunk inclination results in a larger moment arm of the gravitational force acting on \( \text{COM}_{\text{UB}} \) with respect to L5S1, but because of the downward directed exerted hand force (and upward directed reaction force) the moment arm of the hand force with respect to L5S1 is decreased \([48, 50]\). The combination of the
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direction of the hand force and the amount of inclination of the trunk affects the low-back load as reflected in the net moment at L5S1 joint in the sagittal plane. This causes the differences in the biomechanics of pushing at shoulder and hip height and makes clear that handle height has an essential role when studying pushing tasks.

Besides the effect of the direction of hand force and trunk posture on the trunk moment in the sagittal plane, the horizontal component of the hand forces also determines the magnitude and direction of the trunk moment in the transverse plane. In Figure 1-3A, the reaction force in the backward direction at the left hand produces an external moment at the low back in the counterclockwise direction, which requires an internal moment in the clockwise direction and vice versa for force at the right hand. When pushing in a static situation, symmetrical force exertion of left and right hands is assumed at the handles, consequently the external twisting moment at the L5S1 joint equals zero, and therefore, no internal moments are required.

Figure 1-3: Representation of a subject pushing a cart with exerted hand forces at the left hand (A) and with asymmetrically exerted hand forces (B). The arrows represent the reaction force in backward direction at hands. The big and small black circular arrows represent external moments. The empty circular arrows represent internal moments.
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At the workplace, both static and dynamic pushing activities can be observed. In dynamic pushing activities, objects, like wheeled carts, are displaced by pushing and walking at the same time. Generally, in regular walking, angular momentums of the upper and lower body vary in counterphase [10], which implies that the push-off forces at the feet created to walk contribute to the moment at the low back in the transverse plane. In addition, the push-off forces may also result in asymmetric exerted forces at the hands during pushing while walking. As the exerted forces are asymmetric between left and right hands, the twisting moment at the low back is also affected. For instance, in Figure 1-3B, the larger reaction force at the left hand produces a larger counterclockwise directed external moment at the low back compared to the smaller reaction force at the right hand. In contrast with the static situation (Fig 1-3A), the internal moments are required to counterbalance the total external moment. This asymmetric internal twisting moment would cause the trunk twisting in the clockwise (right) direction. Therefore, in this case an internal moment in the clockwise direction is required.

The sketch in Figure 1-3B shows that trunk muscles create a twisting moment that is opposite to the moment resulting from the asymmetric reaction forces at the hands. According to the 40th edition of Gray’s Anatomy, there is no single trunk muscle in the lumbar area that solely contributes to trunk twisting. However, the fibers of the external oblique (EO) muscle diverge downward and forward from its origin (the cartilages of the corresponding ribs) to its insertion (iliac crest and anterior aponeurosis) and the fibers of the internal oblique (IO) muscle diverge upward from its origin (anterior iliac crest, inguinal ligament and thoracolumbar fascia) to its insertion (the cartilages of the corresponding ribs and anterior aponeurosis) [113]. From a muscular architectural point of view, the lateral fibers of EO contribute to trunk moments in ipsilateral twisting and contralateral bending and the lateral fibers of IO contribute to trunk motion in contralateral twisting, contralateral bending and flexion [9]. Specifically, right EO and left IO activate together in clockwise (right) twisting moments and vice versa. This suggests that EO and IO muscles are the main contributors to twisting
moments [25, 60, 89] and that these muscles have to be cyclically active during normal gait [12, 51, 60] and thus probably also in dynamic pushing.

**Trunk stability**

In the previous paragraphs the conditions for static equilibrium of the trunk in pushing were discussed. In addition to being in a mechanical equilibrium, the trunk needs to be stable. Stability is defined as the ability of a system to return to its original state around an equilibrium position after a small perturbation. From a mechanical point of view, the equilibrium of a system is stable when potential energy of the system is at its minimum. The trunk can be modeled as an inverted pendulum, which would be in static equilibrium in the upright position (Fig 1-4A), when the net moment (M) caused by gravity on the pendulum is zero. However, maintaining equilibrium in this state is impossible in reality. When an external perturbation, like the wind, exerts left to right force on the pendulum, it causes a θ degree rotation around the axis (Fig 1-4B) and the pendulum's center of mass is displaced to the right of the center of rotation, consequently $dM/dθ$ is positive, which indicates that the system is unstable, as the moment grows with the perturbation magnitude. The pendulum can be stable when a spring is attached to it as the moment produced by the spring acts in the direction opposite to the displacement (Fig 1-4C). When its length changes, a linear spring exerts a force that can be described as $F = -kdl$, and which can be generalized to $M_s$ (the moment created by the spring) = $-k_s dθ$, with $k_s$ representing the spring stiffness. To obtain a stable system, $M_s$ needs to be larger than $M$ ($dM_s/dθ > dM/dθ$), which prescribes a minimum value for the stiffness of the spring. Furthermore, the higher stiffness of the spring, the smaller the displacements of the pendulum upon a perturbation of given magnitude.
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![Figure 1-4: An inverted pendulum without perturbations (A). After a perturbation, the pendulum rotates $\theta$ degree and will fall over due to the moment caused by gravity (B). The inverted pendulum with a spring (C). The inverted pendulum after a perturbation, which causes an increase in the tensile force exerted by the spring, which is a function of the deviation ($\theta$) of the pendulum (D).](image)

The lumbar spine buckles under a load as low as 88 N [20]. Because the trunk weight exceeds 88 N, this implies that muscles around the lumbar spine must contribute the spinal stability and avoid mechanical injury [6, 15, 27, 83, 96]. The lumbar spine can thus be modeled as the pendulum in Figure 1-4 and the trunk muscles as the springs that stabilize the pendulum in its equilibrium position. Therefore, in the spine system, the level of stiffness of ligaments and trunk muscles determine how robust this system is. In other words, a high level of trunk stability is created by that a high level of muscle stiffness required for stabilizing the equilibrium [96, 117].

Bergmark [6] analyzed the mechanical stability of the lumbar spine, representing the stiffness of trunk muscles with the equation: $k = qF/L$ (k: muscle stiffness, $q$: muscle stiffness coefficient, $F$: muscle force, $L$: muscle length).
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In this equation, $q$ is the proportionality constant relating the ratio of muscle force and length to stiffness. Since the actual value varies between muscles, it was used as a dependent variable in this thesis and the value of $q$ at which the trunk would be critically stable is greater than was calculated $q_{\text{crit}}$. Hence, a lower value of $q_{\text{crit}}$ this critical value indicates a larger margin of trunk stability [6, 117]. Using this approach, it was shown that cocontraction of flexor and extensor muscles is required to stabilize the spine in the upright position [16]. In other words, the stability of the trunk depends on trunk muscle activity and the spine is more resistant to perturbation (more robust) when muscle activity is higher [15, 83]. On the other hand, when the demands of the tasks are low, such as in pushing tasks, trunk muscle activity and hence stiffness is relatively low and the spine may become unstable [15, 83]. The low level of trunk activity may not be sufficient to handle large perturbations in trunk equilibrium, which may account for injuries in low-demand tasks, such as in people who sustain a low-back injury when picking up their newspaper from the floor. Similarly, in cart pushing, trunk stability may be threatened by sudden perturbations due to the low level of trunk stiffness before any perturbation occurs.

Effects of perturbations on trunk muscle activity and motion

When human movements are performed in a dynamic environment, internal and external perturbations change the state of the equilibrium and may endanger trunk stability. In order to preserve the equilibrium and constrain the trunk without losing balance, trunk muscles exert forces on the trunk segment. Muscle force is controlled by the central nervous system (CNS). The sensory receptors in the musculoskeletal system detect changes in the equilibrium and convey the state information to the CNS, which initiates feedforward or feedback control in response to the perturbation.

Taking the pendulum as an example (Fig 1-4C), when there is no information about the direction of the external force, the effective way is to increase the stiffness of the springs around the pendulum in advance. Similarly in the spine system, when the CNS does not have sufficient information on upcoming perturbations, the impact of the perturbations imposed to the trunk is reduced by an overall increase in background trunk muscle activity, referred to
General Introduction

as pre-activation. Pre-activation is a continuous muscle activity, which is either unrelated to the occurrence of perturbations (bracing) or generated in preparation of a perturbation, but in absence of knowledge of timing or direction of the impending perturbation [64, 80]. Trunk muscle pre-activation can be observed as co-activation of agonistic and antagonistic muscles, which increases trunk stiffness and enhances stability [8, 28, 32, 65, 66, 130] and limits the angular displacement of the trunk after perturbations [30, 58, 118, 130, 131].

Feedforward control consists of anticipatory postural adjustments, which typically depend on the predictability of the forthcoming perturbation. When the timing, direction and magnitude of the external force are known, the trunk is moved into the opposite direction and the perturbation force will return it to its equilibrium state. Anticipatory postural adjustments (APAs), have been observed as changes in trunk muscle activity preceding voluntary limb movements [5, 40 – 43], dealing with an external object [105, 106] and even in performing manual material handling tasks, such as lifting tasks [22, 125, 127], under predictable circumstances. Simple and typical APAs are observed in limb movement experiments in which moving a limb (arm) causes a reactive moment on the trunk. For example, in arm flexion, the erector spinae is activated before the rectus abdominus muscle to counteract the trunk flexion moment [40 – 43]. This directionality of anticipatory activation is seen not only in ventral/dorsal trunk muscles, but also in lateral trunk muscles in experiments in which a moving object from the side has to be stopped [104, 105].

To clarify the difference between anticipatory activation and pre-activation, anticipatory activation is an instantaneous action, counteracting a forthcoming predictable perturbation. Pre-activation is seen instead of anticipatory activation when timing or direction of perturbation is unpredictable, it is more or less sustained in view of the unpredictability of the timing of the perturbation and aspecific in magnitude and/or direction because of the unknown perturbation force. In both cases, the initial stability of the trunk may be insufficient to handle the actual perturbations. In such circumstances, the CNS initiates feedback control of trunk muscles as reactive adjustment in response to perturbations [35, 118]. Feedback depends on signal transmission from sensors in the periphery, e.g. muscle spindles signaling changes in muscle length and mechanoreceptors in
the hand signaling changes in reaction forces on the hand, as well as more centrally located sensors, (e.g. the vestibular and visual system) to the CNS and from the CNS to the muscle fibers for muscle force generation. Feedback control is therefore, inevitably delayed and the magnitude of the delay reflects how fast the CNS responds to restore the disturbed position to the undisturbed position or, alternatively, to achieve a new stable equilibrium [102]. A typical example can be observed in sudden trunk unloading. Until the external force is suddenly released, agonists are active to counteract this external force and antagonists are inactive. After the force release, antagonists switch on and agonists switch off. This fast reciprocal change in trunk muscle activity probably reflects the effect of trunk muscle reflexes in response to the changes in muscle length as a consequence of the perturbation [18]. A short latency of trunk muscle was also observed when experiencing sudden unloading at the arm [42, 71], probably based on afferents in the arm. Longer latencies between the perturbation and the muscle response may increase the risk of low-back injury [17, 99].

As described above, a perturbation of the trunk can be defined as a disturbance of the original equilibrium state of the trunk. Some perturbations are induced internally and created by self-generated movements, such as moving limbs (arm or leg) or changes in trunk posture. A second type of perturbations is induced externally and is based on an interaction between body and environment, for instance, sitting upright on a chair with uneven legs. Internal and external perturbations can be predictable or unpredictable. For example, trunk rotation and translation in changing gait direction during walking with an early cue and a late cue [92] are internally generated predictable and unpredictable perturbations, respectively. Another example of external predictable and unpredictable perturbations could be catching an object with eyes open and eyes closed [106, 107].

These types of perturbations may also occur at the workplace in pushing tasks (Figure 1-5). For example, workers push a cart to transport objects around the working place. Pushing while walking could be considered as a predictable self-generated perturbation to the trunk. Occasionally, workers may not pay attention to their environment while pushing a cart, risking a collision with someone or something. Suddenly having to stop the cart to avoid a collision
would be an unpredictable, yet self-generated perturbation to the trunk. Experiencing cart movement after overcoming the static friction when initiating pushing a cart would be a predictable externally generated perturbation. Finally, bumping into an obstacle on the floor or pushing a cart over a rough surface would be unpredictable and externally generated perturbations.

Figure 1-5: A scheme of different kinds of perturbations and possible situations in cart pushing that are studied in the different chapters in the present thesis.
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Objectives of this thesis

In this thesis, realistic occupational pushing tasks are simulated in the laboratory, to study self-generated and externally generated, and predictable and unpredictable perturbations to the trunk. As mentioned above, a pushing task is a low-demand task, which is associated with low muscular effort and low trunk stiffness. Consequently, the relatively low level of trunk stability when pushing a high inertia object may increase a potential risk of low-back injury. Responses of trunk muscles to the perturbations in pushing are to be studied in the sagittal and transverse planes considering the biomechanical relation between the exerted hand forces, which are to be perturbed, and the moments at the low back. Therefore, the main objective of this thesis is to study the control of the trunk in anticipation of and response to perturbations of different type (self-generated and externally generated) and predictability (predictable and unpredictable) when pushing a cart at shoulder and hip height.

For the individual chapters, the principal objectives are as follows:

- **In chapter 2:**
  To study the effects of handle height on trunk muscle control in response to the unpredictable perturbation in which a cart suddenly moves forward. In addition, to investigate whether trunk muscle control is affected by the predictability in dealing with the same perturbation.

- **In chapter 3:**
  To investigate whether trunk muscle control is affected by the different types of perturbations when a moving cart suddenly stops.

- **In chapter 4:**
  To investigate the effects of type and predictability of perturbations due to asymmetric hand forces on trunk muscle control in the transverse plane.

- **In chapter 5:**
  To investigate the effects of the predictability of the perturbation due to asymmetric forces at left and right hands in turning a cart on abdominal oblique muscle activity and trunk motion in the transverse plane.
Chapter 2.

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

Published as:

Abstract
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 to hip height before onset resulted in higher trunk inclination after 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.
Sudden unloading in pushing tasks

Introduction

Unexpected sudden loading and unloading of the trunk have been considered as challenges to trunk muscle control [17, 18, 69, 86, 120, 124]. Inadequate responses to the perturbation are considered to be a risk factor for low-back injury [17, 99].

During pushing tasks at the workplace, sudden loading perturbations may occur when a moving wheeled cart is suddenly blocked [69]. 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 [17, 18, 99, 130]. During pushing, relatively low joint moments around the lumbar spine are observed [47]. As low lumbar moments coincide with relatively low trunk stiffness [15], the spine may be at risk during pushing in case of unexpected situations in which the trunk is suddenly unloaded [46, 109]. 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 generalize to this realistic work task.

The mechanical stability of the trunk depends on appropriate muscle control prior to the perturbation and on the responses to the perturbation [17, 18, 84]. In controlled experiments, the muscle responses to sudden loading consist of fast antagonist activation and agonist de-activation [18]. Trunk muscle co-activation (bracing) prior to the perturbation was furthermore shown to reduce the amplitude of trunk displacement in such experiments [8]. In experiments with sudden additional loading, not only co-activation [130], but also higher muscle activity associated with a higher force against an initial external load enhanced trunk stability and reduced response amplitudes after the perturbation [14, 29, 131]. Similarly, in pushing tasks when the cart was blocked, the trunk was less perturbed in conditions with higher trunk muscle pre-activation, that is when pushing at hip height compared to shoulder height [69]. It is still unclear whether this generalizes 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 to pushing at hip height [69]. Therefore, we hypothesized that (1.a) that trunk stability is lower before 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 [50]. The exerted hand forces during a typical dynamic pushing task in which a four-wheeled cart is displaced can be divided into three phases [121]. 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 can’t 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 [64, 80]. 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 onset of movement is smaller in the self-initiated condition.
Sudden unloading in pushing tasks

Methods

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.

Experimental design and procedure

Prior to the start of the experimental pushing activities, participants performed a series of contractions meant to elicit the maximum isometric voluntary contractions (MVC) of each of the trunk muscles studied [82]. Then, participants familiarized themselves with the task of pushing a four-wheeled cart for about 5 minutes. The cart (height 1.6 m, depth 0.8 m, width 0.64 m) weighed 200 kg and had hard rubber wheels (0.028 m wide, 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 2-1).

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 while 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 to 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 randomized.
Figure 2-1: The experimental setup, showing the four-wheeled cart instrumented with two calliper breaks on the front wheels.

**Data acquisition**

Exerted hand forces and kinematic data of light-emitting diode (LED) cluster markers on the upper body segments were collected by 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) and an Optotrak 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
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from the reaction forces at the hands and the anthropology and kinematics of upper body segments, using an inverse dynamic model [57]. Markers on the handles were used to calculate the position of the cart and the onset of cart movement.

Electromyograms (EMG) were recorded by using disposable Ag/AgCl surface-electrodes (Blue Sensor; lead-off area 1.0 cm², 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™, TMS, Enschede, The Netherlands; input impedance > 10¹²Ω, 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 [68].

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 normalize the EMG signals.

Data analyses for effects of handle height in the externally triggered condition (hypothesis 1)

The effects of handle height on amplitudes of trunk muscle EMG, trunk internal moment and trunk inclination were determined. After normalization 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 activity of the second before cart movement were considered as the baseline values.
To analyze trunk stability prior to cart movement an EMG driven model was used [115, 126, 128]. The EMG-driven model consisted of 164 muscle slips crossing the L5-S1 joint and has been described in more detail previously. The 16 normalized 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 3-D linked segment model and muscle moments was obtained by optimizing the maximum tension in the muscles. Subsequently, muscle forces were estimated as the outcome of the optimal muscle maximum tension, normalized EMG amplitude and correction factors for the instantaneous muscle length and contraction velocity [56]. The dependent variable was the \( q_{crit} \), calculated based on the joint stability index for the sagittal plane \( (S_y) \) proposed by Potvin and Brown [96]:

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

In the equations, 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 [96]. The \( q_{crit} \) is the value of \( q \) at which the trunk would be critically stable in the given configuration [117]. 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 lower values interpreted as a larger margin of stability.
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To determine changes after the onset of movement, the peak values of internal sagittal plane moments, trunk inclination, abdominal and back muscle activity observed in the first second after movement of the cart were determined. Subsequently, the difference 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) prior to perturbations in this condition. Bilateral MU, LI, 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 generalized likelihood ratio algorithm [114]. Corrections of onset and offset times were made as needed based on visual inspection by a single observer.

Data analyses for 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 activity 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.
Statistics

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

Statistical analyses for hypothesis 1

The baseline values of internal moment, trunk inclination, abdominal and back muscle activity and \( q_{\text{crit}} \) 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 we compared between pushing at shoulder height and hip height.

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 values of \( q_{\text{crit}} \), trunk inclination, and abdominal and back muscle activity. Finally, to compare reactions to the perturbations, muscle responses and changes in trunk inclination were tested for differences between conditions.

Results

Effects of handle height in the externally triggered condition

A typical example of the data of one participant is shown in Figure 2-2. 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 1s 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
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trunk inclination were nearly constant.

At the group level, the average internal moment (5.62 SD 20.97 Nm at shoulder height and -33.29 SD 21.57 Nm at hip height) and trunk inclination (14.09 SD 5.92° at shoulder height and 26.85 SD 13.89° at hip height) during one second 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 prior to the start of the cart movement were around 3% MVC and were not significantly different between handle heights (Figure 2-3 and Table 2-1). For back muscle activity, as expected, the EMG amplitude prior to 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).

Figure 2-2: 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.
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 2-4). The back muscle activity reached 8.50 (SD 5.12) and 13.36 (SD 7.80) %MVC 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 was 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 2-4). Summarizing, the EMG onset times and offset times were around 200 ms and 500 ms and changes in flexor and extensor muscle activity were at approximately 1% and 5 %MVC, in contrast with our hypothesis, not significantly different between shoulder height and hip height (Table 2-1). In line with our hypothesis, however, the maximum changes of internal moment
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and trunk inclination after the cart movement were significantly larger at shoulder height (-23.10 SD 12.91 Nm and 4.36 SD 2.48 °) than at hip height (-11.58 SD 6.86 Nm and 1.84 SD 1.85 °) (Figure 2-3 and Table 2-1).

Figure 2-4: 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.
Table 2-1: Results of the paired-samples t test to determine the differences between shoulder height and hip height.

<table>
<thead>
<tr>
<th>Paired-samples t test</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>(shoulder height vs. hip height)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>t (10)</td>
<td>p</td>
</tr>
<tr>
<td>$q_{crit}$</td>
<td>4.345</td>
<td>.001</td>
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<tr>
<td></td>
<td>t (10)</td>
<td>p</td>
</tr>
<tr>
<td>Internal moment</td>
<td>3.987</td>
<td>.003</td>
</tr>
<tr>
<td>Trunk inclination</td>
<td>-3.213</td>
<td>.009</td>
</tr>
<tr>
<td>Abdominal muscle activity</td>
<td>-0.336</td>
<td>.744</td>
</tr>
<tr>
<td>Back muscle activity</td>
<td>-4.661</td>
<td>.001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Left side</th>
<th>Right side</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>t (10)</td>
<td>p</td>
</tr>
<tr>
<td>EMG onset time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MU</td>
<td>-1.470</td>
<td>.172</td>
</tr>
<tr>
<td>LL</td>
<td>-1.871</td>
<td>.091</td>
</tr>
<tr>
<td>IL</td>
<td>0.283</td>
<td>.783</td>
</tr>
<tr>
<td>IT</td>
<td>1.329</td>
<td>.213</td>
</tr>
<tr>
<td>LT</td>
<td>0.268</td>
<td>.794</td>
</tr>
<tr>
<td>EMG offset time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td>-0.408</td>
<td>.692</td>
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<tr>
<td>OI</td>
<td>0.438</td>
<td>.671</td>
</tr>
<tr>
<td>OE</td>
<td>-1.399</td>
<td>.192</td>
</tr>
</tbody>
</table>

Significant $p$-values are indicated in bold. Negative t-values indicate higher values in pushing at hip height, except for the internal moment, where due to the negative values of the change of moment negative t-values indicate higher values in pushing at shoulder height.

**Effects of expectation of cart movement**

Given the finding above that pushing at shoulder height appears more sensitive to the perturbation caused by 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 2-5. The vertical solid line is the instant that the cart started to move. As 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
Sudden unloading in pushing tasks

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).

Figure 2-5: 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.

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 2-2). This difference can be explained by the EMG amplitudes of abdominal and back muscles prior to the cart movement, which is shown in Figure 2-6. 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, while 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 2-6 and Table 2-2).

Figure 2-6: 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.

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

<table>
<thead>
<tr>
<th>Paired-samples t test</th>
<th>t (10)</th>
<th>p</th>
</tr>
</thead>
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<td>q_{crit}</td>
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<td>.003</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th></th>
<th>Baseline</th>
<th>Peak</th>
<th>Maximum change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdominal muscle activity</td>
<td>2.578</td>
<td>.028</td>
<td>-1.015 .334 -3.711 .004</td>
</tr>
<tr>
<td>Back muscle activity</td>
<td>3.759</td>
<td>.004</td>
<td>-1.048 .319 -3.161 .010</td>
</tr>
<tr>
<td>Trunk inclination</td>
<td>-0.124</td>
<td>.904</td>
<td>-1.080 .306 -1.550 .152</td>
</tr>
</tbody>
</table>

Significant p-values are indicated in bold. Negative t-values indicate higher values in the externally triggered condition.
Sudden unloading in pushing tasks

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 generalize 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 hypothesized, prior to cart movement, lower $q_{crit}$ and higher trunk extensor muscle activity were observed in pushing at hip height compared to pushing at shoulder height. Furthermore, after 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 was 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 prior to 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 cart movement. Trunk muscle activity reached similar levels of activity after cart movement, suggesting that larger changes occurred in the externally triggered condition.

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, 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 [17, 18]. 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 [17, 18, 99]. This may be due to differences in the kind of imposed perturbation. In the present study the perturbation was applied to the hands while 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 [42], most likely the slower responses can be explained by the slower drop in the external moment in the present realistic task than in previous experiments. The onset and offset times varied widely (Figure 2-4), 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 to hip height nor were they activated faster. Compared to pushing at hip height, the baseline level of back muscle activity was lower and the $q_{crit}$ prior to the perturbation was higher at shoulder height. This indicates a lower level of trunk stiffness when pushing at shoulder height compared to pushing at hip height, due to lower pre-activation of the back muscles when pushing at shoulder height. In absence of quick muscle responses compensating for the lower stability of the trunk, ensuing motions may exceed safe boundaries [18]. Indeed, larger changes in trunk inclination after sudden unloading were observed at shoulder height compared to 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 opposite direction, were observed when a cart was blocked during pushing [69]. Taken together these findings suggest an increase in potential injury risk due to unexpected changes in cart movement when pushing at shoulder height.

The constant pushing force prior to the sudden release of the brakes suggests that participants did not 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 prior to the perturbation and that all parameters changed only after the perturbation.
Sudden unloading in pushing tasks

The $q_{\text{crit}}$ was calculated based on 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 3-D linked segment model. The internal moments averaged over both heights were estimated at 29.63 Nm by the EMG-driven model and 29.84 Nm by the dynamic 3-D linked segment model. The root-mean-square (RMS) error between these moment estimates ranged over participants from 1.14 to 13.87 Nm. Hence, the estimated $q_{\text{crit}}$ does suffer from estimation errors. The RMS errors, however, were not different between conditions and, moreover, conclusions based on $q_{\text{crit}}$ were in accordance with EMG amplitudes.

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, prior to the onset of cart movement, higher abdominal and back muscle activity was found in the self-initiated condition compared to the externally triggered condition. These results indicate a higher level of trunk muscle cocontraction that increases trunk stiffness (lower $q_{\text{crit}}$). Participants knew the cart was not locked in the self-initiated condition, which apparently triggered such preparatory cocontraction, similar to that in sudden loading experiments in which the participant is warned for an impending perturbation [63, 64, 80]. Because of this preparatory trunk cocontraction, a low risk for low-back injuries would be expected after sudden, yet anticipated, unloading during pushing. Indeed after onset of cart movement the peak trunk inclination was smaller in the self-initiated than the externally triggered condition, though not significantly so. 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. Generalization to other populations, such as experienced manual material handlers or females should, therefore, be considered with care.

**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 due to 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 cocontraction of trunk muscles served to increase trunk stiffness in anticipation of cart movement. The preparatory cocontraction of trunk muscles in this situation may reduce the risk of low-back injury.

**Acknowledgement**

We thank for Marit Balder for her assistance in data acquisition.
Chapter 3.

Control of trunk motion following sudden stop perturbations during cart pushing

Published as:

Abstract
External perturbations during pushing tasks have been suggested to be a risk factor for low-back symptoms. An experiment was designed to investigate whether self-induced and externally induced sudden stops while pushing a high inertia cart influence trunk motions, and how flexor and extensor muscles counteract these perturbations. Twelve healthy male participants pushed a 200 kg cart at shoulder height and hip height. Pushing while walking was compared to situations in which participants had to stop the cart suddenly (self-induced stop) or in which the wheels of the cart were unexpectedly blocked (externally induced stop). For the perturbed conditions, the peak values and the maximum changes from the reference condition (pushing while walking) of the external moment at L5/S1, trunk inclination and electromyographic amplitudes of trunk muscles were determined. In the self-induced stop, a voluntary trunk extension occurred. Initial responses in both stops consisted of flexor and extensor muscle cocontraction. In self-induced stops this was followed by sustained extensor activity. In the externally induced stops, an external extension moment caused a decrease in trunk inclination. The opposite directions of the internal moment and trunk motion in the externally induced stop while pushing at shoulder height may indicate insufficient active control of trunk posture. Consequently, sudden blocking of the wheels in pushing at shoulder height may put the low back at risk of mechanical injury.
Unexpected stops in pushing tasks

Introduction

Pushing has been associated with the risk of low-back pain [21, 37, 46, 94]. This is remarkable since in pushing, joint moments around the lumbar spine are low [47]. However, these low moments probably coincide with a relatively low trunk stiffness [14, 118], which may put the spine at risk of mechanical injury when trunk perturbations occur [15], especially given the high inertia of objects handled in industrial pushing tasks [13, 91].

When pushing a cart, perturbations of the trunk may occur because of sudden stops. One may, for example, be required to suddenly stop the cart to avoid a collision. The high inertia of the transported object may in this case impose a sudden, yet self-induced, flexion perturbation of the trunk similar to that when lifting an unexpectedly heavy object [125]. Alternatively, sudden stops may occur due to an external event, for example when an obstacle blocks the wheels. In contrast to the self-induced stop, this may impose an external trunk extension moment due to high reaction forces at the hands. Both situations may perturb trunk movement, which could be a cause of injury.

When experiencing unpredictable continuous perturbations during pushing while walking [68] and lifting [129], participants respond by stiffening the trunk using cocontraction. The objective of the present study was to investigate how trunk motion and trunk muscle activity are controlled in relation to unexpected sudden stops during pushing. We hypothesized that both types of sudden stops (self-induced and externally induced) could lead to uncontrolled trunk motions, i.e. an increase in trunk inclination due to an external flexion moment during self-induced stops and a decrease in trunk inclination due to an external extension moment during externally induced stops. Additionally, we hypothesized that trunk inclination would be more affected when sudden stops occur during pushing at shoulder height than at hip height. As higher trunk moments and hence higher muscle activity would be present prior to the perturbation when pushing at hip height [48]. Furthermore, we hypothesized that trunk flexor and extensor muscles would co-contract in response to perturbations in both types of sudden stops.
Chapter 3

Methods

Participants

Twelve healthy male volunteers (age 30.2 (SD 5.4) years, height 1.86 (SD 0.06) m and weight 79.4 (SD 8.1) 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.

Procedure

Prior to start the experimental pushing activities participants performed a series of contractions meant to elicit the maximum isometric voluntary contractions (MVC) of each of the trunk muscles studied [82]. Then, participants familiarized themselves with the task of pushing a cart for about 5 minutes. The four-wheeled cart (height 1.6 m, depth 0.8 m, width 0.64 m) weighed 200 kg and had hard rubber wheels, (0.028 m wide, diameter 0.124 m). The two wheels nearest to the subject could swivel. Force transducers were attached to the two handles, at the subject’s shoulder height (acromion angle) or hip height (upper border of greater trochanter). Participants pushed the cart while walking over a 5m distance at a self-selected speed, which was considered as the reference trial. For the perturbation conditions, the participants pushed the cart at their self-selected speed, but in case of the self-induced stopping conditions an auditory stop cue, played at a constant volume during the experiment by a computer, was given at mid-stance phase of the right foot after walking over a 2.5m distance. Participants were instructed to stop the cart as fast as possible after the cue. For the externally induced stop, the cart was caused to bump into an obstacle, which was a metal bar (length 63 cm, height 2.8 cm, width 7 cm) attached to the cart just in front of the front wheels, which was released by an electromagnet at mid-stance of the right foot (Figure 3-1). To avoid the participants becoming aware of the perturbation conditions, several reference trials were performed before each perturbed condition. The sequence of the tasks, i.e. two perturbation conditions (self-induced stop and externally induced stop) at two pushing heights (shoulder and hip heights), was randomized.
Unexpected stops in pushing tasks

Figure 3-1: The experimental setup, which the four-wheeled cart instrumented with an electromagnetic device holding an obstacle in front of the front wheels.

Data collection and analysis

Electromyograms (EMG) were recorded using disposable Ag/AgCl surface-electrodes (Blue Sensor; lead-off area 1.0 cm², inter-electrode distance 2.5 cm). After abrasion and cleaning with alcohol, electrodes were bilaterally attached over internal oblique (3 cm medial to the anterior superior iliac spine (ASIS)), external oblique (halfway the axial line between the 10th rib and the ASIS), rectus abdominis (3 cm lateral to the umbilicus), multifidus (2 cm lateral to L4/L5), longissimus thoracis pars lumborum (3 cm lateral to L3), iliocostalis lumborum (6 cm lateral to L2), iliocostalis thoracis (6 cm lateral to T11) and longissimus thoracis pars thoracis (3 cm lateral to T10). EMG signals were band-pass filtered (10 - 400 Hz), amplified (20 times, Porti-17™, TMS, Enschede, The Netherlands; input impedance > 10¹²Ω, common mode rejection ratio > 90 dB) and stored on disk (sample rate 1000 samples/s; 22 bits). ECG contamination was identified by means of independent component analysis and removed from the signals [68]. 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 normalize the EMG signals. The sample rate was off-line reduced to 50 samples/s using a running average. After normalization with the MVC values, bilateral internal oblique, external oblique and rectus abdominis EMG amplitudes were averaged to represent abdominal muscle activity and multifidus, longissimus thoracis pars lumborum, iliocostalis lumborum, iliocostalis thoracis and longissimus thoracis pars thoracis were averaged to represent back muscle activity during the whole trial time series.

Exerted hand forces and kinematic data of LED cluster markers on the upper body segments were collected by 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) and an Optotrak 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 feet and at the handle of the cart. Marker positions were recorded at 50 samples/s. The external 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 (trunk inclination), using an inverse dynamic model [57]. Markers on the feet were used to monitor the gait pattern during the trials, detect mid-stance of the right foot on-line for triggering of the auditory stop cue or obstacle release and calculated the self-selected walking speed before stopping cart push.

To study the control of the trunk motion in response to the sudden stops, trunk inclination and external moments at the L5/S1 in the sagittal plane were analyzed for the first second after the cue occurred, the obstacle was released, or after the mid-stance phase of the right foot after walking over a 2.5m distance in the reference trail. Five random reference trials were averaged to represent the reference condition. The change in trunk inclination, was analyzed relative to the upright posture, which was defined as zero degrees. For each condition, the peak value of external sagittal moments, trunk inclination, abdominal and back muscle activity during the one-second time series was determined. In the reference
Unexpected stops in pushing tasks

condition, the range from mean plus to minus one standard deviation was considered as the normal range of pushing while walking. Subsequently, the difference between the peak in the perturbed conditions and the edge of the normal range at the same instant in the one-second time series was considered as the maximum change due to the perturbation.

Statistics

Data were checked for normality before statistically analysis using an ANOVA for repeated measure. As all data appeared to be right skewed, data were logarithmically transformed.

First, in order to assess whether participants reduced their speed to prepare for stopping the cart in the perturbed conditions, the self-selected walking speeds in the different pushing tasks were compared in an ANOVA for repeated measures. Furthermore, to analyze the differences between the perturbed conditions and the reference condition, within subject contrasts were used. The differences between the reference condition and the perturbed conditions were explored using two-way ANOVAs for repeated measures with the peak values of external moments, trunk inclination, abdominal and back muscle activity as dependent variables and pushing condition (pushing while walking, self-induced stop and externally induced stop) and handle height (shoulder and hip height) as independent variables.

The differences between the self-induced and externally induced stops were further explored using two-way ANOVA for repeated measures with the maximum change of the same dependent variables and the type of stop (self-induced stop and externally induced stop) and handle height as independent variables. Simple effects were screened separately by using type of stop or handle height as the independent variable to perform one-way ANOVAs for repeated measures. Bonferroni adjustment was used for pairwise comparisons. For all statistical tests, p values < 0.05 were considered as statistically significant.
Chapter 3

Results

The mean self-selected walking speed during all pushing tasks was 1.17 ms$^{-1}$ (SD 0.15). The walking speed during the reference condition was not different from the walking speed just before the perturbations (1.16 ± 0.13 ms$^{-1}$ vs 1.18 ± 0.16 ms$^{-1}$; F(1,11)=0.52, p=0.604).

ANOVA for repeated measures on the log transformed data showed significant effects of condition (reference and two sudden stops) on the peak values of external moment, trunk inclination and trunk muscle EMG (Table 3-1). Compared to the reference condition, the peak extension moment was approximately 30 Nm higher in the externally induced stop and the peak flexion moment was approximately 40 Nm higher in the self-induced stop ($p<0.05$). The trunk was approximately 10 degrees less inclined during both perturbation types compared to the reference condition ($p<0.01$). The EMG amplitudes were approximately 20 and 10 %MVC higher in the self-induced and externally induced stops, respectively, than in the reference condition ($p<0.01$). Additionally, trunk inclination and back muscle activity were affected by pushing height, i.e. both were higher at hip height than at shoulder height.

Table 3-1: Results of the two-way ANOVA for repeated measures with pushing condition (pushing while walking, self-induced stop and externally induced stop) and handle height (shoulder or hip height) as factors performed for the peak values of the external moment, the trunk inclination, the abdominal muscle and back muscle EMG amplitudes. PW = pushing while walking, SS = self-induced stop, ES = externally induced stop.

<table>
<thead>
<tr>
<th>Two-way ANOVA</th>
<th>Conditions (PW, SS, ES)</th>
<th>Handle height</th>
<th>Conditions × height</th>
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<tbody>
<tr>
<td></td>
<td>F (2,22)</td>
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<td>F (1,11)</td>
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<tr>
<td>Moment</td>
<td>11.93</td>
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<tr>
<td>Trunk inclination</td>
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<tr>
<td>Abdominal muscle</td>
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<tr>
<td>Back muscle</td>
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<td>14.16</td>
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<table>
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<th>ES vs. PW</th>
</tr>
</thead>
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<td>Moment</td>
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</tr>
<tr>
<td></td>
<td>11.90</td>
<td><strong>0.005</strong></td>
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<tr>
<td>Trunk inclination</td>
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<tr>
<td>Abdominal muscle</td>
<td>159.32</td>
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<tr>
<td>Back muscle</td>
<td>75.21</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Significant $p$-values are indicated in bold.
**Unexpected stops in pushing tasks**

A typical example of the data of one subject is shown in Figure 3-2. The data are presented for pushing the cart at shoulder height in three conditions. The cue for the self-induced stop and the externally induced stop occurred at mid-stance of the right foot and data are presented for 1 second after this instant. During unperturbed pushing, the hand forces, the external moment at the L5/S1, the trunk inclination and the EMG amplitudes of the abdominal and back muscles were all nearly constant (dotted line (mean) and gray area (plus/minus 1 SD)). For the self-induced stop, in response to the auditory cue, the subject exerted a downward directed pulling force (Figure 3-2A). As expected, an increase in the external flexion moment at L5-S1 was observed outside the normal range from about 20 Nm to about 65 Nm. However, in contrast with our hypothesis, this coincided with a decrease in trunk inclination from about 20 degrees to about 10 degrees (Figures 3-2B & 3-2C). In the externally induced stop, the pushing force increased, which coincided with an external extension moment and the hypothesized decrease in inclination (Figures 3-2A, 3-2B & 3-2C).
Figure 3-2: Typical example of one subject pushing 200 kg at shoulder height in the pushing while walking (PW), during self-induced stop (SS) and externally induced stop (ES) conditions. The dotted lines and gray area represent the means and standard deviation (SD) of PW. The thin and wide black lines represent ES and SS, respectively. The solid and dashed lines of the hand force represent the exertions in the horizontal and the vertical directions. The solid and dashed lines of EMG represent muscle activation as percentage of MVC of the abdominal muscles and back muscles. Arrows indicate the positive directions.
Unexpected stops in pushing tasks

Similar patterns of the external moment during self-induced and externally induced stops were found at group level at both heights (Figure 3-3). Also for the trunk inclination, the average patterns of the group during both stops were similar to the example, except that only small changes occurred in both sudden stops when pushing at hip height.

Figure 3-3: Means and standard deviation (SD) of moment, trunk inclination and EMG amplitudes at group level. The dotted lines and gray area represent the means and SD between participants in pushing while walking (PW). Means and SD (error bars) with thin and wide black lines represent the externally induced stop (ES) and self-induced stop (SS) conditions, respectively. The positive and negative parts of the external moment and trunk inclination represent the flexion and extension direction, respectively. The solid and dashed lines of EMG represent muscle activation as percentage of MVC of the abdominal muscles and back muscles. Arrows indicate the positive directions. The left and right portions represent pushing at shoulder and hip height, respectively.

To compare the two types of sudden stops, the maximum changes from the reference data are shown in Figure 3-4 and the statistical analysis is summarized in Table 3-2. Changes in external moments had opposite signs between self-induced and externally induced stops. The maximum change in trunk inclination was significantly affected by an interaction between type of stop and pushing height. When pushing at shoulder height, type of stop significantly affected the maximum change in trunk inclination, which was larger in the externally induced
stop than in the self-induced stop. When pushing at hip height, type of stop did not affect the maximum change in trunk inclination. Additionally, in the externally induced stop, the maximum change in trunk inclination was larger when pushing at shoulder height than at hip height.

Figure 3-4: Maximum changes of the external moment, trunk inclination and EMG amplitudes of abdominal muscles and back muscles during the externally induced stop (ES) and self-induced stop (SS) conditions. The positive and negative parts of the external moment and trunk inclination represent the flexion and extension direction, respectively. The upper and lower panels represent pushing at shoulder and hip height, respectively.

As shown in the example (Figure 3-2), about 200 ms after the auditory instruction to stop the cart, both the abdominal and back muscles became more active. After about 400 ms, only abdominal muscle activity decreased, while back muscle activity was sustained. The changes in trunk muscle activity were initially similar, but trunk muscle activity occurred faster in the externally induced stop than in the self-induced stop. Furthermore, trunk muscle activity decreased to values close to normal in both abdominal and back muscles within about 400 ms after onset (Figure 3-2D). Similar muscle activity patterns were observed at group level and at both heights (Figure 3-3). The increases in abdominal and back muscle activity were 9.52 and 8.21 %MVC higher in the self-induced stop than in the externally induced stop (Table 3-2 & Figure 3-4).
Unexpected stops in pushing tasks

Table 3-2: Results of the two-way ANOVA for repeated measures with type of stop (self-induced stop and externally induced stop) and handle height (shoulder or hip height) as factors performed for the maximum change of the external moment, trunk inclination, the abdominal muscle and back muscle EMG amplitudes. For trunk inclination, effects of the pushing condition were evaluated by one-way ANOVA. The mean differences between conditions and heights were evaluated by Pairwise comparisons. SS = self-induced stop, ES = externally induced stop.

<table>
<thead>
<tr>
<th>Two-way ANOVA</th>
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<th>Type of stop x height</th>
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<table>
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<th>Hip – Shoulder Mean difference</th>
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<tr>
<td>Moment (Nm)</td>
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<td>.397</td>
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<td>Trunk inclination (degree)</td>
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<td>.173</td>
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<td>Abdominal muscle (%MVC)</td>
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<td>.259</td>
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<td>Back muscle (%MVC)</td>
<td>8.21</td>
<td><strong>.031</strong></td>
<td>7.78</td>
<td><strong>.013</strong></td>
</tr>
</tbody>
</table>

One-way ANOVA (dependent variable: trunk inclination)

<table>
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<tr>
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<th>Mean difference (degree)</th>
<th>p</th>
</tr>
</thead>
<tbody>
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<td>At shoulder height</td>
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<td>4.65</td>
<td><strong>.011</strong></td>
</tr>
<tr>
<td>At hip height</td>
<td>1.77</td>
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<td>.210</td>
</tr>
<tr>
<td>Factor: handle height</td>
<td></td>
<td>(Hip – Shoulder)</td>
<td></td>
</tr>
<tr>
<td>Self-induced stop</td>
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<td>.476</td>
</tr>
<tr>
<td>Externally induced stop</td>
<td>5.01</td>
<td>4.25</td>
<td><strong>.047</strong></td>
</tr>
</tbody>
</table>

Significant p-values are indicated in bold.

Discussion

The present study was designed to investigate how trunk inclination and trunk muscle activity are controlled after sudden stops while pushing a cart at walking speed. In the self-induced stop, an external flexion (internal extensor) moment coincided with a decrease in trunk inclination. In contrast, the externally induced stop appeared to cause an involuntary trunk motion, a decrease in trunk inclination due to an external extension (internal flexor) moment. Smaller changes in trunk inclination occurred when pushing at hip height compared to pushing at shoulder height. After the cue was given, or after an obstacle blocked the cart, activity of both trunk flexor and extensor muscles...
increased, indicating that participants initially cocontracted the trunk muscles in response to the perturbations.

In the self-induced stop, the external flexion moment did not increase trunk inclination as we had anticipated. Instead a voluntary extension movement was observed. After cocontraction of extensor and flexor muscles, extensor activity was sustained, reflecting directionally specific muscle activity, which corresponded to an internal extensor moment generating the change in trunk inclination. The initial nonspecific trunk muscles response (cocontraction) might reflect a startle response [97]. The subsequent directionally specific muscle response was similar to that seen in participants after being tripped while walking [123]. Throughout the self-induced perturbation condition, muscle activity levels and moments were relatively low. Hence, spinal loading appears limited in these conditions. Because of this low load level and the absence of involuntary movement, a low risk for low-back injuries would be expected after sudden, yet self-induced, perturbations during pushing.

After an externally induced stop, a perturbation of trunk posture in the expected (extension) direction occurred. The decreased inclination that coincided with the external extension moment indicated that the unexpected (externally induced) perturbations directly caused trunk motion. The sudden stop affected the trunk inclination less during pushing at hip height. Compared to pushing at shoulder height, the larger trunk flexion prior to the perturbation gives a larger margin of safety until extreme joint motions could be reached. Furthermore, the higher trunk muscle activity that coincides with this posture, likely causes higher trunk stiffness, which may explain the smaller changes in trunk inclination. It has previously been shown that with higher preloading, external perturbations have less effect on trunk posture [14, 118]. Our findings suggest a potential injury risk at the low-back in the externally induced stop during pushing at shoulder height. Although averaged over participants trunk inclination remained in flexion when pushing at shoulder height, the standard deviation indicates a large variation between participants (Figure 3-4). Indeed, in four participants the trunk was declined backwards after the sudden stop. These participants might be at risk of injury as gravity would further perturb their trunk posture. These four participants showed less trunk inclination than
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the other participants before the perturbations and lower moments after the perturbation.

During the present experiment, self-selected speed was not different between the perturbed conditions before the perturbations occurred and the reference condition. This suggests that participants did not anticipate the sudden stops. The unexpectedness of these stops was also confirmed by the fact that the external moments, trunk inclination and EMG amplitudes reached values outside of the normal range (mean±SD) only after the stop cue was given, or the obstacle was released. In the present study, pushing forces were in the range of what has been observed in practice [46]. The self-induced stop can be compared to situations in many working conditions, in which workers are required to stop suddenly to avoid collisions. Although participants were instructed to stop as fast as possible after the cue, they may have delayed their response to optimize foot placement before stopping the cart, which may explain the delay in responses after the cue was given. Appropriate muscle control in the self-induced stop may not generalize to larger amplitude perturbations, such as when pushing a heavier cart or when walking faster than in the present study. The externally induced stop in the present study resembles real situations, in which obstacles may block the cartwheels. The present study involved young healthy male participants only. Generalization to other populations should, therefore, be considered with care.

Conclusion

In conclusion, our results show that appropriate muscle control caused voluntary trunk extension in self-induced sudden stops of pushing a cart, while externally induced stops caused uncontrolled trunk motion in the extension direction during pushing at shoulder height. This finding points at a potential risk for low-back injury in pushing tasks.

Acknowledgements

We thank Sjoerd M. Bruijn for his crazy and explosive shouting played in the experiment, Marit Balder for her assistance in data acquisition and Gert S. Faber for his assistance in data analysis.
Chapter 3
Chapter 4

Oblique abdominal muscle activity in response to external perturbations when pushing a cart

Published as:

Abstract

Cyclic activation of the external and internal oblique muscles contributes to twisting moments during normal gait. During pushing while walking, it is not well understood how these muscles respond to presence of predictable (cyclic push-off forces) and unpredictable (external) perturbations that occur in pushing tasks. We hypothesized that the predictable perturbations due to the cyclic push-off forces would be associated with cyclic muscle activity, while external perturbations would be counteracted by cocontraction of the oblique abdominal muscles. Eight healthy male subjects pushed at two target forces and two handle heights in a static condition and while walking without and with external perturbations. For all pushing tasks, the median, the static (10th percentile) and the peak levels (90th percentile) of the electromyographic amplitudes were determined. Linear regression models with oblique abdominal EMGs and trunk angles as input were fit to the twisting moments, to estimate trunk stiffness. There was no significant difference between the static EMG levels in pushing while walking compared to the peak levels in pushing while standing. When pushing while walking, the additional dynamic activity was associated with the twisting moments, which were actively modulated by the pairs of oblique muscles as in normal gait. The median and static levels of trunk muscle activity and estimated trunk stiffness were significantly higher when perturbations occurred than without perturbations. The increase baseline of muscle activity indicated cocontraction of the antagonistic muscle pairs. Furthermore, this cocontraction resulted in an increased trunk stiffness around the longitudinal axis.
Trunk control in pushing tasks

Introduction

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 (LBP) [109]. However, pushing and pulling activities can also contribute to the risk of LBP [21, 37, 46, 94]. The load at the low-back is determined by the external forces at the hands in combination with the posture and movements of the upper body [50]. Compared to pulling, low-back moments around the transverse plane are lower during pushing, because of opposite moment directions produced by hand forces and gravitational loading [23, 47, 62, 72]. Because of these low moments during pushing, trunk stiffness will be relatively low, which may put the spine at risk of mechanical injury [15], especially given that unpredictable perturbations frequently occur during pushing due to irregularities of the floor or due to poorly functioning wheels and given the high inertia of objects that are transported [13, 15, 109].

When pushing while walking both the push-off forces created to walk as well as hand forces due to irregularities in rolling resistance may perturb the trunk around its longitudinal (twisting) axis. In normal gait, angular momentum of upper and lower body vary in counterphase [10]. This implies that trunk muscles create a twisting moment that is opposite to the moment resulting from the push-off forces. External oblique (EO) and internal oblique (IO) muscles are the main contributors to twisting moments [25, 60, 89] and these muscles are cyclically active during normal gait [12].

In contrast to the predictable cyclic push-off forces, forces at the hands may vary unpredictably because of irregularities in rolling resistance as mentioned above. When experiencing unpredictable hand loads during lifting, subjects responded by stiffening the trunk by cocontraction [127, 129]. Therefore, the objective of the present study was to investigate how trunk motion and EO and IO muscle activity are controlled in relation to the time-varying twisting moments that occur during pushing a cart in situations without and with perturbations. We hypothesized that in pushing while walking EO and IO would be cyclically active. In addition, we hypothesized that unpredictable perturbations applied to the cart would cause increased cocontraction of EO and
IO muscles and thus increased tonic muscle activity, to stiffen the trunk around its longitudinal axis.

**Methods**

**Participants**

Eight healthy male volunteers (age 26.4 (SD 7.8) years, height 1.82 (SD 0.05) m and weight 79.4 (SD 8.8) kg) participated in the experiment after signing an informed consent. Subjects reported no history of LBP or other musculoskeletal disorders within the past 12 months. The ethics committee of the Faculty of Human Movement Sciences approved the experiment.

**Procedure**

Prior to the actual experiment, subjects performed maximum isometric voluntary contractions (MVC) of the trunk muscles [82]. Before starting experimental pushing activities, subjects familiarized themselves with the task of pushing a cart on a treadmill for about 5 minutes. The four-wheeled cart (height 1.6 m, depth 0.8 m, width 0.64 m) weighed 85 kg and had hard rubber wheels with 0.032 m width and 0.12 m diameter. The two wheels nearest to the subject could swivel. On the treadmill, the rolling resistance between the cart and the surface at 0.8 m s⁻¹ (3 km h⁻¹) was 15 N. Force transducers were attached to the two handles, which were fixed on the cart at the subject’s shoulder height (acromion angle) or hip height (upper border of greater trochanter). The required horizontal component of the pushing force (target force) was predetermined at 75 N and 150 N [46] by suspending weights from two ropes that were attached at the left and right side of the cart running backwards over a pulley mechanism (Figure 4-1).
Trunk control in pushing tasks

Figure 4-1: The experiment setup of the four-wheeled cart on the treadmill and the ropes of the pulley system behind the subject used to manipulate target forces.

Subjects pushed while standing still, pushed while walking, and pushed while walking with perturbations. For pushing while standing, the subjects pushed the cart for two steps (on the treadmill that was not running) to lift the weights at the end of the ropes from the ground and maintained this position. For pushing while walking the subjects had to push the cart on the treadmill running at 3 km h⁻¹, while keeping the weights at the end of the ropes from the ground. For the perturbation condition the subjects again pushed the cart on a running treadmill, but in this condition the experimenter (the same person for all subjects) manually produced perturbations by repeatedly pulling the ropes. The pulling of the left and right side ropes resulted in continuous pseudo-random perturbations with a relatively low-frequency content and the magnitude and frequency content of the forces applied were assumed to be the same between subjects. Subjects were aware which trials would have perturbations, but the timing and whether forces would be applied to the left or right side were unpredictable. The sequence of the twelve activities, i.e. three
pushing conditions (static, pushing while walking without and with perturbations), two pushing heights (shoulder and hip height) and two target forces (75 N and 150 N) was randomized.

Data collection and analysis

Electromyography (EMG) was recorded using disposable Ag/AgCl surface-electrodes (Blue Sensor; lead-off area 1.0 cm², inter-electrode distance 2.5 cm). After abrasion and cleaning with alcohol, electrodes were attached over the left and right internal oblique (LIO & RIO: 3 cm medial of the anterior superior iliac spine (ASIS) just proximal of the inguinal ligament) and external oblique (LEO & REO: half of axial line between 10th rib and the ASIS). EMG signals were band-pass filtered (10 - 400 Hz), amplified (20 times, Porti-17™, TMS, Enschede, The Netherlands; input impedance > 10¹²Ω, common mode rejection ratio > 90 dB) and stored on disk (sample rate 1000 samples/s; 22 bits). ECG contamination was identified by means of independent component analysis (ICA) and removed from the signals. In short, heart rate was estimated from the mean of all EMG signals after 8-18 Hz bandpass filtering. Subsequently an ICA was performed on all raw EMG signals using fastica [53] and the components (1 or 2) that showed peaks close to the estimated heart rate were identified and set to zero. The signals were then reconstructed from the modified set of independent components by an inverse ICA. 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 MVC trials were processed using the same steps and the maximal values were used to normalize the EMG signals. The median, static level (P10, 10th percentile) and the peak level (P90, 90th percentile) of the normalized EMG signals were determined [54].

Exerted hand forces and kinematic data of LED cluster markers on the upper body segments were collected by 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) and an Optotrak system (Northern Digital, Waterloo ON, Canada), respectively. Force data were stored at 800 samples/s and synchronized with the kinematic data. Clusters consisted of four LED markers attached to a 100 × 100 mm metal plate on a double hinge joint,
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which allowed orienting the metal plate to optimize marker visibility. Marker positions were recorded at 50 samples/s. Clusters were placed on the pelvis, thorax, bilateral upper arms and forearms and additional markers were placed at the head and handles of the cart.

A dynamic 3-D linked segment model, described in detail by Kingma et al. [57], was used to calculate net moments at the level of the L5S1 intervertebral disc. The current, slightly modified model uses anthropometrical data according to McConville and Churchill [81], combined with data of exerted hand forces and kinematics of the upper body segments. The hand force signals were transformed to the global axis system and low pass filtered at 2 Hz (bidirectional second-order Butterworth). The reaction forces on the hands, the kinematics of the upper body, the mass and location of the centre of mass of the upper body segments were used as inputs in a global equation of motion, as described by Hof [44], to calculate the net moment at the L5-S1 intervertebral disc. The sample rate was reduced to 25 Hz using a running average. Amplitudes of trunk twisting angles and moments were expressed as root mean square values.

To study the control of trunk muscle activity in relation to the time-varying twisting moments at the pelvis and to estimate trunk stiffness, a relationship between the EMG of the oblique muscles and the twisting moment was determined using the following model:

\[
\text{Moment}(t) = \beta_1 \cdot \text{LEO}(t) + \beta_2 \cdot \text{REO}(t) + \beta_3 \cdot \text{LIO}(t) + \beta_4 \cdot \text{RIO}(t) + \beta_5 \cdot \theta(t)
\]

where \(\beta_1 \sim \beta_4\) are model coefficients, \(\tau\) is the time delay between EMG and moment production and \(\theta\) is angular displacement between thorax and pelvis and \(\beta_5\) reflects trunk axial stiffness. The model was progressed an optimization approach by Matlab function (fmincon) and fit to the data by minimizing the root mean square error with the twisting moment that was determined by inverse dynamics. The model was fit for time delays from 0-1000 ms (0-25 samples). Subsequently the time delay for which model fit was best was chosen as the optimal outcome. Model coefficients were the design variables of which the time delay was constrained to be positive and less than half of a period of the moment signal and model coefficients were constrained to have a sign in accordance with
the mechanical function of each muscle (e.g. LEO and RIO were constrained to produce positive moments). For each of the experimental conditions the EMG data were fit separately because of expected changes in posture and, hence, muscle length and EMG-force relationships.

Statistics

The objective was to study how trunk twisting motion and oblique abdominal muscle activity are controlled in response to the time-varying twisting moments during pushing while walking and during pushing with unpredictable perturbations. First, it was tested whether the amplitudes of the twisting moments and twisting angles were affected by walking versus pushing while standing, handle height and target force using an ANOVA for repeated measures.

Control of the oblique abdominal muscle activity was explored by determining the cumulative probabilities of the EMG amplitudes for each of the four muscles, which visualizes the effect of walking versus pushing while standing and pushing while walking with perturbations versus without perturbations on the distribution of the EMG signals. An ANOVA for repeated measures was performed to determine whether pushing while walking compared to pushing while standing, handle height and target force affected the P10 and median values of the EMG distributions. In pushing while standing, the P90 EMG activity represents the maximum activity required for the sagitally symmetric pushing task. When walking while pushing adds only a dynamic component (no increase in cocontraction), the static level of EMG activity (P10) should be similar to the P90 in pushing while standing. This was tested by comparing the P90 EMG activity (%MVC) in pushing while standing to the P10 EMG activity during pushing while walking using an ANOVA for repeated measures.

The effect of perturbations during pushing while walking was further explored using ANOVAs for repeated measures with twisting moment, twisting angle, median and P10 values of the EMG distributions of the oblique muscles, model coefficients of the muscles ($\beta_1$-$\beta_4$, i.e. moment producing capacities) and trunk twisting stiffness ($\beta_5$) as dependent variables and the presence of
Trunk control in pushing tasks

perturbations, handle height and target force as independent variables. Bonferroni correction was used for post-hoc testing. For all statistical tests, $p$ values $< 0.05$ were considered as statistically significant.

Results

A typical example of a trial is shown in Figure 4-2 presenting data from one subject pushing a 150N target force at shoulder height during pushing while standing (Figure 4-2A), pushing while walking without perturbations (Figure 4-2B) and with perturbations (Figure 4-2C). Obviously, during pushing while standing the twisting moment, twisting angle and EMG amplitudes were nearly constant. During pushing while walking without perturbations, LEO&RIO and REO&LIO were activated cyclically in correspondence with the twisting moment. On average, the twisting moment amplitude was only 2.80 Nm and trunk twisting excursion was only 0.34 degrees during pushing while standing, which was significantly lower than when walking (Figure 4-3; Table 4-1).
Figure 4-2: Typical example of one subject pushing at a target force of 150 N at shoulder height in the pushing while standing condition (A), during pushing while walking without (B) and with (C) perturbations. The upper panels represent the observed time-varying twisting moments and the moments predicted by the linear model. The middle panels represent the twisting angles. The positive parts of the lower panels represent muscle activation as percentage of MVC of the LEO and RIO as synergists and the negative parts represent values of REO and LIO (multiplied by -1). The horizontal lines represent the P10 for each muscle. LEO = left external oblique, REO = right external oblique, LIO = left internal oblique, RIO = right internal oblique.
Table 4-1: Results of the ANOVA for repeated measures with pushing condition (standing or walking), handle height (shoulder or hip height) and target force (75N or 150N) as factors performed for the twisting moment, twisting angle and the EMG amplitudes of the four oblique abdominal muscles. LEO = left external oblique, REO = right external oblique, LIO = left internal oblique, RIO = right internal oblique.

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Significant p-values are indicated in bold.
When pushing while walking was perturbed, more irregular trunk moments and trunk motions occurred (Figure 4-2C). In addition, the baseline activity of the muscles increased, consistent with the expected cocontraction, as is obvious in Figure 4-2C. Overall, the twisting moment amplitudes were significantly higher when perturbations were imposed than without perturbations (Figure 4-3; Table 4-2). The cumulative probability distributions of the EMG amplitude during pushing while walking with perturbations shifted to higher values compared to without perturbations (Figure 4-4). Consequently, the median EMG amplitudes of the oblique muscles, except the RIO, were significantly higher with than without perturbations (Figure 4-5; Table 4-2). In addition, for all muscles, except the RIO, also the P10 values during pushing with perturbations were significantly higher than during pushing without perturbations (Figures 4-4 and 4-5; Table 4-2).

![Figure 4-3](image_url)

**Figure 4-3:** Means and standard deviations (error bars) of the twisting moment and twisting angle amplitudes. The first, second and third groups in each plot present pushing while standing, pushing while walking without perturbations and with perturbations, respectively. The bars present the conditions during pushing at shoulder height (S) with 75 N (white), S with 150 N (light gray), hip height (H) with 75 N (dark gray) and H with 150 N (black).
Trunk control in pushing tasks

Figure 4-4: The cumulative probability distributions of the EMG amplitudes of four oblique muscles when pushing at a target force of 150 N at shoulder height, averaged over subjects. The dotted lines represent pushing while standing. The dashed lines represent pushing while walking without perturbations. The solid lines represent pushing while walking with perturbations. The solid horizontal bars represent standard deviations of P90 during pushing while standing. The wider solid horizontal bars represent standard deviations of P10 during pushing while walking without perturbations. LEO = left external oblique, REO = right external oblique, LIO = left internal oblique, RIO = right internal oblique.

The increased P10 levels are consistent with an increase in cocontraction of the muscle pairs that produce left (REO & LIO) and right (LEO & RIO) twisting moments. To determine whether this resulted in an increased stiffness of the trunk around its longitudinal axis, a model with EMG activity of the oblique abdominal muscles and the twisting angle as input signals was fit to the moment data. Examples of twisting moment calculated by the dynamic 3D linked segment model and predicted by the linear model are shown in Figure 4-2. The estimate of trunk twisting stiffness ($\beta_5$) was significantly affected by the presence of perturbations (Table 4-2 and Figure 4-6). Overall, estimated stiffness was 0.90 Nm/degree during pushing while walking without perturbations and 2.25 Nm/degree when perturbations were imposed. The stiffness was not affected by interactions between handle height, target force and pushing condition or perturbations. Model coefficients $\beta_1 \sim \beta_4$, reflect the moment producing
capacities of LEO, REO, LIO and RIO. These were expected to vary with height and target force, as changes in these generally coincide with changes in posture and hence muscle lengths. Only a small, significant effect of the presence of perturbation on $\beta_2$, the moment producing capacity of the REO was found, while the other coefficients were not affected, as would be expected (Table 4-2).

Figure 4-5: The bars and error bars present means and standard deviations of the EMG amplitudes of four muscle during pushing at shoulder height (S) with 75 N (white), S with 150 N (light gray), hip height (H) with 75 N (dark gray) and H with 150 N (black). The white dots represent the values of the P10 amplitudes. The first, second and third groups in each plot represent pushing while standing, pushing while walking without perturbations and with perturbations, respectively.
Trunk control in pushing tasks

Table 2. Results of the ANOVA for repeated measures with pushing while walking (with or without perturbation), handle height (shoulder or hip height) and target force (75N or 150N) as factors performed for the twisting moment, twisting angle, stiffness (β₅), the EMG amplitudes and model coefficients (β₁-β₄) of the four oblique abdominal muscles. LEO = left external oblique, REO = right external oblique, LIO = left internal oblique, RIO = right internal oblique. β₁-β₅ refer to model coefficients of the linear model relating EMG amplitudes and twisting angle to the twisting moment.

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Significant p-values are indicated in bold.
Figure 4-6: Means and standard deviations (error bars) of axial trunk stiffness during pushing without and with perturbations in the left and right portions, respectively. The bars present stiffness during pushing at shoulder height (S) with 75 N (white), S with 150 N (light gray), hip height (H) with 75 N (dark gray) and H with 150 N (black).

Discussion

The present study was designed to investigate how trunk twisting motion and oblique abdominal muscle activity are controlled in reaction to the time-varying twisting moments that occur during pushing a cart while walking with perturbations. When perturbations occurred, median and static levels of trunk muscle activity and estimated trunk stiffness were significantly higher than without perturbations, suggesting that subjects co-contracted the abdominal muscles in response or in anticipation of the perturbations.

In the present study, when pushing while walking, the total range of twisting movement was approximately minus 4.5 degrees to plus 4.5 degrees, which appears smaller than in normal gait (approx. 12 degrees, Huang et al. submitted). In contrast, the range of twisting moments was approximately -10 to +10 Nm, which appears to be substantially higher than in normal gait [59]. Also the EMG amplitudes of EO and IO were at 11% and 18% MVC somewhat higher than observed during walking without arm swing [12]. The moments and EMG
activity showed a cyclic pattern, corresponding with the gait cycle. Static level muscle activity (P10) during pushing while walking was not higher than the peak level (P90) in pushing while standing (Figure 4-4). In the pushing while standing condition, oblique abdominal muscle activity produced spinal moments in the sagittal plane only as twisting moments were close to zero. The static level muscle activity in dynamic pushing, which equalled the peak level in pushing while standing thus appeared to be necessary to produce these moments when pushing while walking, while the additional dynamic activity was associated with the twisting moments, which were actively modulated by the pairs of EO and IO muscles, as in gait [12, 60]. Trunk twisting moments in normal gait cause an angular momentum of the upper body opposite to that of the lower body [10].

In two-handed cart pushing, trunk as well as arm movements are constrained, which likely accounts for the lower movement amplitudes. The presence of (asymmetric) hand reaction forces in pushing may explain the higher moments as well as the higher EMG amplitudes as compared to normal gait.

In the present study, the perturbations imposed were disturbances of the hand forces and can be compared to situations in which a cart is moved over an irregular surface or when cartwheels malfunction. In the presence of these perturbations, higher EMG amplitudes of oblique abdominal muscles were observed. The higher static level of muscle activity (P10) indicates that the muscles maintain a higher level of baseline activity during the tasks [54]. This implies an increase in cocontraction of the antagonistic muscle pairs (LEO&RIO and REO&LIO), similar to the increased cocontraction of flexor and extensor muscles during lifting while experiencing unpredictable perturbations [129]. The modelling results furthermore indicated that this resulted in higher trunk stiffness around the longitudinal axis. This increased stiffness may be an effect of the higher cocontraction level, causing increased axial compressive load on the spine which increases its stiffness [30]. Additionally, while short-range muscle stiffness [98] may not be effective against the relatively slow perturbations in the current experiment, muscles operating on the ascending limb of their force-length relationship will provide more resistance against perturbations at higher levels of activation, which would be be reflected as an increased stiffness [122]. Increased stiffness is a feedforward mechanism to counteract unpredictable
perturbations. In addition, phasic oblique abdominal activity was clearly visible in response to perturbations (see Figure 4-2). In spite of these increases in muscle activity, trunk motions were increased by the perturbations, indicating a potential injury risk for larger amplitude perturbations [73, 77].

The present study involved young healthy male subjects only. Generalization to other populations should, therefore, be considered with care.

The model used to fit the relationship between trunk muscles and moments was strongly simplified, assuming linear EMG force relationships and ignoring the effect of other muscles on twisting moments. The root-mean-square (RMS) error and r-square between the observed and the predicted moment from the models ranged from 3.93 to 10.01Nm and 40 to 50%, respectively. Hence, stiffness estimates will suffer from some substantial estimation errors. These errors, however, are expected to be random and, moreover, results of stiffness estimates were corroborated by evidence of increased cocontraction from EMG.

**Conclusion**

In conclusion, our results show that the contralateral EO and ipsilateral IO muscles actively modulate trunk twisting moments when pushing while walking. When pushing is perturbed, axial trunk stiffness is increased by cocontraction of these muscles. The observed patterns of muscle control are not completely successful in preventing increased twisting movements in the lumbar spine.

**Acknowledgements**

Wilmien Slaghuis is greatly acknowledged for her assistance in data acquisition.
Chapter 5.

Trunk muscle control in response to (un)expected turns in cart pushing

Under review:

Abstract

Before altering the travel direction in normal gait, anticipatory activation in trunk muscles is observed, followed by a top-down sequence of rotation of body segments. Turning while pushing a cart is a more challenging task for the trunk because of its low stiffness in pushing while walking and the interaction with the high inertia of the cart. Twelve healthy subjects pushed a 200 kg cart at shoulder and hip height while making turns (gradual, sharp and unexpected sharp). The baseline values of trunk rotator muscle activity before the turn and the peak values after the turn were determined. Additionally, peak values of hand forces, twisting moments and twisting motions were assessed. Rotator muscle activity was significantly higher than in pushing without turning only before a gradual or sharp turn. After the turn, clockwise twisting motion was associated with a clockwise twisting moment induced by the reaction forces at the left hand. Anticipatory activation was initially absent in the unexpected sharp turn, while bilateral trunk rotator muscle activity increased after the turn, indicating co-contraction. In the unexpected turn condition the combination of an uncontrolled twisting motion with delayed muscle activation may increase the potential risk of low-back injury.
Chang direction in cart pushing

Introduction

Turning during walking challenges the dynamic equilibrium of the human body because of the requirement to translate and rotate the body towards the new direction of travel. When initiating a turn in normal gait, a top-down temporal sequence is shown in initiation of rotation of body segments [1, 2, 39, 92]. In planned turns, foot placement in the preceding steps is modified to initiate the shift of the body center of mass [92, 93, 134], while when having to make a turn unexpectedly, subjects may stop first and only then change direction [39, 93].

Pushing while turning in transporting patients has been studied from the perspective of trunk loading in relation to the association between pushing tasks and low-back pain [76]. Pushing tasks frequently entail handling objects with a high inertia and unpredictable mechanical interactions with this object and the environment. At the same time, low trunk loading and consequently low trunk muscle activity and trunk stiffness may render control over trunk posture and movement problematic [14, 68, 69, 118]. Trunk control in pushing while turning has to our knowledge not been studied previously.

In turning during normal walking early activation of trunk extensor muscles was found [39]. This suggests that anticipatory activation is used to control the trunk as in postural perturbations in upright standing [104, 105, 107]. When performing voluntary movements such as rapid arm movements, anticipatory activation of trunk muscles is directionally specific [5, 43], which was also observed in dealing with an external object, such as when stopping a moving object [104, 105] or lifting a box with known inertial properties [125, 127]. Also, anticipatory activation was scaled with respect to object properties in lifting [22]. In turning while pushing, the perturbing moment on the trunk will mainly be a twisting moment. We, therefore, hypothesize that trunk rotator muscles are activated directionally specific prior to making a preplanned turn while pushing a cart, i.e. left rotator muscles are more active when turning to the left, and scaled with respect to task demands, i.e. activity is higher when making a sharp turn than a gradual turn.

In cart pushing, sudden turns may be required to avoid a collision. This may not allow sufficient time for anticipatory trunk muscle activation. This could lead
to loss of control over trunk movement, which in other types of perturbations appeared to be counteracted by a subsequent, co-contraction of trunk muscles [70, 107]. Therefore, our hypothesis was that following a sudden turn trunk rotator muscles would co-contract.

Methods

Subjects

Twelve healthy volunteers (seven females and five males) participated in the experiment after signing an informed consent. Subjects (age 29.4 (SD 4.3) years, height 1.76 (SD 0.08) m and weight 73.4 (SD 11.5) kg) 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.

Experimental design and procedure

Subjects performed a series of contractions meant to elicit the maximum isometric voluntary contractions (MVC) of each of the trunk muscles studied [82]. Then, subjects were familiarized with the experimental tasks by approximately 5 minutes of practice trials of gradual and sharp turns with the four-wheeled cart to the left into a 1 m wide path (Fig. 5-1). The cart (height 1.6 m, depth 0.8 m, width 0.64 m) weighed 200 kg and had hard rubber wheels (0.028 m wide, diameter 0.124 m). The two wheels nearest to the subject could swivel. Force transducers were attached to the handles of the cart.

Subjects pushed the cart from standstill over a distance of about 2.5 m at self-selected walking speed at shoulder (acromion angle) and hip (upper border of greater trochanter) height, then make a gradual or sharp turn to the left (90°). For an unexpected turn, subjects were instructed to perform a sharp turn as fast as possible after an auditory cue, which was played by a computer at mid-stance of the left foot. Before the unexpected trial, a random number of (4 to 6) straight pushing trials (without turning) was performed to avoid that subjects would anticipate making the turn. The sequence of the tasks, i.e. three turns (gradual, sharp and unexpected sharp) at two pushing heights (shoulder and hip heights), was randomized.
Figure 5-1: The experimental setup with the four-wheeled cart. The width of the path is 1 m (black tapes on the floor and two boxes). The two boxes are fixed on the floor and used to ensure that the cart was reoriented 90° to the left direction.

**Data acquisition and analysis**

Electromyograms (EMG) were recorded with disposable Ag/AgCl surface-electrodes (Blue Sensor; lead-off area 1.0 cm², 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)), lateral external oblique (LOE: halfway along the axial line between the 10th rib and the ASIS), and anterior external oblique (AOE: cross point of a horizontal line through the umbilicus and a vertical line through the ASIS). EMG signals were band-pass filtered (10 - 400 Hz), amplified (20 times, Porti-17™, TMS, Enschede, The Netherlands; input impedance > 10¹²Ω, common mode rejection ratio > 90 dB) and stored on disk (sample rate 1000 samples/s; 22 bits). ECG contamination was identified by means of independent component analysis and removed from the signals [65]. 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 normalize the EMG signals.

Hand forces and kinematic data of LED cluster markers on the upper body segments were collected by 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) and an Optotrak system (Northern Digital,
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Waterloo ON, Canada), respectively. Force data were stored at 1000 samples/s and then reduced to 50 samples/s using a running average. Clusters with three LED markers were placed on the pelvis, thorax, bilateral upper arms and forearms. Marker positions were recorded at 50 samples/s. The external moment at the L5-S1 intervertebral disc was estimated from the reaction forces at the hands and the anthropometry and kinematics of the upper body segments, using an inverse dynamics model [57]. Additional markers on the heels and on the handles were used for timing the auditory cue to make an unexpected sharp turn and to calculate position and orientation of the cart.

The onset of change in left hand forces was used to align the data of the three types of turns. The normalized EMG amplitudes of left (right) LOE, AOE, and right (left) OI were averaged to represent left (right) rotator muscle activity. The average rotator muscle activity over 200 ms prior to the onset was considered as the baseline value, to study the state of anticipatory activation in the different types of turn compared to straight pushing.

To study effects of the types of turn on trunk motion in the transverse plane and the trunk muscle control in response to the unexpected perturbation, we focused on the initiation of the turn, which was defined from the onset to 1.2 s later. The peak values of hand forces, twisting moment, twisting motion and EMG amplitudes of bilateral rotators observed during this period were determined.

Statistics

For evaluating directionally specific anticipatory activation, a three-way (side (left and right) × turn: no, gradual, sharp and unexpected sharp)× handle height (shoulder and hip)) repeated measures ANOVA was performed on the baseline values of EMG amplitudes of left and right rotators. Using simple contrasts, the baseline data of each type of turn was compared to the data of straight pushing. Two-way (type of turn × handle height) repeated measures ANOVAs were performed on the peak values of hand force, twisting moment and twisting motion. The other three-way (side × type of turn × handle height) repeated measures ANOVAs were performed on the peak values of EMG amplitudes. Bonferroni adjustment was used for subsequent pairwise comparisons. For all statistical tests, p values < 0.05 were considered as statistically significant.
Chang direction in cart pushing

Results

A typical example of pushing while turning (-0.4~4.2 s) is shown in Figure 5-2. Unlike the cart, which directly rotated counterclockwise until around 90°, the trunk and pelvis rotated clockwise up to around 1.2~1.8 s, followed by a counterclockwise rotation (Fig 5-2A, 5-2B, 5-2C). In combination with the COM displacement in the medial-lateral plane, this indicates that the upper body moved towards the right before turning to the left (Fig 5-2D, 5-2E, 5-2F). In all types of turns after about 1.2 s to 1.8 s, the trunk led the pelvis in rotating counterclockwise. In the unexpected sharp turn, trunk rotation clearly proceeded pelvis rotation between 0 s and 0.4 s compared to the sharp turn. Hence, the following analyses were restricted to -0.4 s to 1.2 s.

Before the turn, the baseline value of left (right) rotator muscle activity (Fig 3) was 2.89 SD 1.30 (3.54 SD 2.16) %MVC in the gradual turn and 3.38 SD 1.71 (3.39 SD 2.04) %MVC in the sharp turn, which were significantly higher than in the straight pushing (left: 2.07 SD 1.11 %MVC and right: 2.13 SD 1.10 %MVC) (p<0.05). In contrast, the baseline values of left and right rotators were not different between the unexpected sharp turn (2.47 SD 0.99 %MVC and 2.68 SD 1.25 %MVC) and straight pushing. This implies that higher trunk rotator muscle activity is only observed when subjects expect to make a turn. However, in none of the conditions a difference between left and right rotators was observed, indicating that the anticipatory activation in the gradual and sharp turns was not directionally specific.
Figure 5-2: Typical example of a subject pushing 200 kg at shoulder height in the gradual turn, sharp turn and unexpected sharp turn. The angular displacements of the cart (thin black line), trunk (fat gray line) and pelvis (fat black line) in the global system are illustrated in the upper panels (A, B, C). The upper body center of mass (COM) in the mediolateral (M-L) plane in the global system is displayed in the lower panels (D, E, F).

After the onset, the obvious differences in direction and magnitude between left (backward, right, downward) and right (forward, right, upward) hand forces suggest that the left hand dominates in steering the cart to the left (Fig 5-4). At the group level (Fig 5-3), the type of turn significantly affected the peak of the hand forces ($p<0.01$). The magnitudes of hand force were smallest for the gradual turn, but not different between the expected and unexpected sharp turn, except for the vertical component of the left hand ($p<0.01$).
Chang direction in cart pushing

Figure 5-3: Means and standard deviation (error bars) of handle height in gradual turn (white), sharp turn (dark gray) and unexpected sharp turn (black). The peak value of hand force, trunk twisting motion, trunk twisting moment and EMG amplitudes are represented at group level. The baseline values of EMG amplitude are represented at group level in straight pushing (light gray) and three types of turn. The symbols (*) represent the p-value being smaller than 0.05.

A clockwise twisting moment corresponded with the backward and right directed force at the left hand, which coincided with a clockwise twisting motion (Fig 5-4). Type of turn significantly affected the magnitudes of both twisting moment and motion (p<0.01). Larger twisting moments and motions were observed in the expected (-54.50 SD 24.17 Nm and -10.37 SD 4.82°) and unexpected sharp turn (-62.79 SD 30.57 Nm and -10.11 SD 6.34°) than in the gradual turn (-18.75 SD 11.78 Nm and -6.14 SD 4.03°) (Fig. 5-3). Post-hoc analyses showed that the peak twisting moment and twisting motion were not significantly different between the expected and unexpected sharp turn, which suggests that the trunk experiences a similar perturbation. However, the slope of twisting motion (the onset to the peak) was steeper in the unexpected sharp turn,
indicating a higher movement velocity in the unexpected sharp turn compared to the sharp turn (Fig 5-4).

Figure 5-4: Typical example of a subject pushing 200 kg at shoulder height in the gradual turn (dash lines), sharp turn (thin black lines) and unexpected sharp turn (wide black lines). The vertical lines represent the onset of left hand force change (0 s). The vertical dashed lines represent the 0.4 s prior to the onset. Left and right hand force are presented for the three directions, separately. The data of trunk twisting motion and twisting moment are presented in the pelvis system. EMG amplitudes represent muscle activation as percentage of MVC of the left and right rotator muscles. For the EMG panels, gray lines represent muscle activity in the straight pushing.

Left and right rotator muscle activities increased gradually after 0 s in the sharp turn and steeply after 0.4 s in the unexpected sharp turn (Fig 5-4). On group level (Fig 5-3), the maximum values of left and right rotator muscle activity in the unexpected sharp turn (9.94 SD 5.84 and 11.57 SD 6.87 %MVC) were significantly higher than in the sharp turn (7.38 SD 4.59 and 9.22 SD 6.09 %MVC) (p<0.01). In none of the turns was the EMG amplitudes significantly different between left and right rotators, implying that co-contraction of trunk rotators occurred in response to the perturbation induced by turning the cart.
Chang direction in cart pushing

Overall, only twisting motion was significantly affected by handle height \((p<0.05)\). The amplitude was approximately \(2^\circ\) larger when pushing while turning at shoulder height.

Discussion

Based on literature on turning in normal walking we expected an early counterclockwise rotation of the trunk in turning while pushing a cart. However, initially the trunk twisted clockwise, which was a direct consequence of the interaction with the cart. This movement appears to be planned because not only was it observed in the gradual turn, it also was part of an overall movement to the right to position the body behind the cart in its new travel direction.

When subjects expected to make a turn, the baseline trunk rotator muscle activity was significantly higher than in straight pushing, suggesting that this activity is increased in anticipation of the turning task. However, baseline EMG amplitudes were not significantly different between left and right rotators. In retrospect, given the direction of trunk rotation, higher muscle activity of the right rotators compared to the left rotators at baseline would be expected. Turning the cart was, however, achieved by creating a backward and right directed force with the left hand. The reaction forces caused a clockwise-directed twisting moment on the trunk, which apparently was the direct mechanical cause of the twisting motion. Increased baseline activity might thus be aimed at controlling this motion by increasing trunk stiffness around the longitudinal axis by cocontraction of both trunk rotators [68]. In addition to twisting movements, trunk lateral bending occurs when turning in normal walking [92]. From a muscular architectural point of view, OE and OI are synergists for trunk twisting motion, but antagonists for trunk lateral bending [9]. Therefore, lateral bending movement and the related need to counterbalance the lateral bending moment due to gravity, might also explain why the anticipatory activation before turning was not directionally specific. However, only small and inconsistent lateral bending movements and moments were observed in the present conditions, possibly due to the constraint imposed by holding the handles of the cart. The smaller amplitude of twisting motion when pushing at hip height compared to shoulder height, may reflect an increased stiffness of the trunk in the more
forward inclined posture, which coincides with overall higher trunk muscle activity [69, 70].

After the turn, the twisting moment due to the interaction with the cart apparently caused a clockwise rotation, which in the gradual and sharp turns was resisted by the anticipatory co-activation of the rotator muscles. In the unexpected sharp turn, left and right rotator muscles were activated only well after the turn, implying that the trunk initially twisted clockwise by the external moment without direct control of this movement by trunk musculature. This coincided with faster trunk rotation and, subsequently, a larger increase in muscle activity was observed compared to the sharp turn.

While trunk rotation moments were the dominant component of trunk loading in both expected and unexpected turns, anticipatory trunk rotator activity preceding expected turns and trunk rotator activity after the turns was not significantly different between the left and right rotators. Possibly, stiffening the trunk through muscle co-contraction before and during turning was preferred, in view of the partial unpredictability of the interactions with the cart, which may be affected by irregular friction. Similarly, in lifting loads with unknown and unpredictable mechanical properties trunk muscle co-contraction has been observed [127, 129].

The present study is, to our knowledge, the first study to investigate trunk control during pushing while turning. Baseline EMG amplitudes (around 3% MVC) in the straight pushing condition were lower than reported in a previous study (around 7% MVC when pushing on a treadmill against a 75N target force). The lower cart load resulting in a lower hand force, may explain this. On the other hand, low levels of coactivation between agonists and antagonists can yield substantial stiffness of the trunk [16]. Additionally, the asymmetric hand forces for altering direction of the cart caused substantial twisting moments, which were much higher than those caused by asymmetric perturbations applied in the previous study [68]. In the unexpected sharp turn, the similar baseline activity for straight pushing indicates that the auditory cue for making a turn was indeed unexpected. This is also supported by the large backward and downward directed peak hand forces in this condition, which indicate a strategy to decelerate the cart before or while making the turn.
Chang direction in cart pushing

In the present study, variability due to measurement error can be expected to be relatively low based on previous studies using similar methods [10, 11]. Only one trial was performed for each type of turn, therefore variation in behaviour within subjects over repeated trials remains unknown, but may have limited statistical power. However, study power appeared to be sufficient in general. The experimental design consisted of left turns into a 1 m wide path only. However, the gradual and sharp turns in the present study would be expected to cover most of the range of turns that occur in practice. Although the present study involved young healthy subjects only without professional experience in pushing tasks, pushing tasks are common daily activities, e.g. when using a shopping cart in a supermarket. Hence, we believe that studying this task in non-expert performers addresses a relevant target group and we expect limited differences with real experts.

Conclusion

When the turn is preplanned, increases in bilateral trunk rotator activity as anticipatory activation probably control the twisting motion after initiating a turn by increasing trunk stiffness around the longitudinal axis. On the contrary, the absence of anticipatory activation in the unexpected condition resulted in increases in trunk rotation velocity and trunk rotator activity increased bilaterally to levels above the level seen in planned turns. Mainly hand forces on the side to which the subject turns are used to decelerate the cart and steer it in the new direction. The subjects first turn themselves in the opposite direction before turning in the desired direction back to align with the cart in the travel direction. Because the subject’s trunk is twisted due to the moment caused by the interaction with the cart, the uncontrolled trunk rotation and delayed trunk muscle responses may put the lumbar spine at risk of injury when unexpectedly having to change the direction of a cart.
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Epilogue
Objectives and main findings

The studies in this thesis were designed to investigate the control of trunk muscle activity and trunk motion before and after perturbations in cart pushing at different handle heights. As mentioned in the general introduction (chapter 1), perturbations were classified into four subgroups: predictable and unpredictable perturbations, either self-generated or externally generated (Fig 1-5). These perturbations were described in this thesis in relation to different phases during cart pushing, i.e. when starting or stopping to push a cart, when walking while pushing a cart or when making a turn while pushing a cart (Fig 6-1).

Figure 6-1: Schematic representation of the chapters of the present thesis based on the division in predictability of the perturbation (upper – predictable; lower – unpredictable) and type of perturbation (left – self generated; right – externally generated).
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The principal objectives of the studies were: (1) to study the effects of predictable perturbations on the control of trunk muscle activity and trunk motion before the actual occurrence of the perturbations (upper quadrants in Fig 6-1), (2) to compare the effects of predictable and unpredictable perturbations on the control of trunk muscle activity and trunk motion after the occurrence of the perturbations (comparison of upper and lower quadrants in Fig 6-1), and (3) to compare the effects of self-generated and externally generated perturbations on trunk motion after the occurrence of the perturbations (comparison of left and right quadrants in Fig 6-1). Additionally, we aimed (4) to study differences in trunk muscle control and trunk motion in response to the perturbations when pushing at shoulder height or hip height.

The main findings of the studies in this thesis were:

➢ The predictability of the perturbation affects trunk muscle activity in pushing a four-wheeled cart. Trunk muscle activity (extensor/flexor muscles in chapter 2 and rotator muscles in chapter 5) is increased to enhance the trunk stiffness in anticipation of the perturbation.

➢ After the occurrence of unpredictable perturbations in pushing a four-wheeled cart, trunk stiffness in the sagittal plane (chapter 2 & chapter 3) and in the transverse plane (chapter 4 & chapter 5) is increased by cocontraction of trunk muscles.

➢ The internal moment at the low back was opposite to the direction of trunk motion in response to unpredictable and externally generated perturbations, which may reflect uncontrolled trunk motion in the sagittal and (chapter 2 & chapter 3) transverse (chapter 5) planes.

➢ When pushing a cart at shoulder height, lower trunk muscle activity was observed before the perturbation and a larger displacement of trunk motion in the sagittal (chapter 2 & chapter 3) and transverse (chapter 4 & chapter 5) planes was observed after the perturbation compared to pushing at hip height.
Trunk responses before and after perturbations

Sudden perturbations of the trunk are considered a risk factor for low-back injury [15, 17, 109]. If the perturbations in cart pushing are predictable, does the trunk respond differently in comparison with pushing tasks without the perturbations and does the trunk protect itself against such perturbations? In the studies of the present thesis, similar trunk motions with higher trunk muscle activity were observed before expected perturbations compared to the same tasks without the perturbations. Trunk muscles showed anticipatory activation or pre-activation in response to predictable perturbations. Anticipatory activation was observed prior to self-initiated starts of pushing a four-wheeled cart and pre-activation of trunk muscles was observed during pushing while walking and before making a gradual or sharp turn while pushing. Antagonistic cocontraction of trunk muscles appeared to be initiated to increase trunk stiffness and to achieve a relatively high level of trunk stability to handle the impending perturbation. This aspecific preparation for the perturbations in cart pushing was comparable with that following a warning before an impending sudden external loading perturbation of which the timing is not exactly known [63, 64, 80] and differed from the specific anticipatory actions prior to lifting a box with load knowledge [22, 125, 127] or before catching a moving object with visual control [104, 105]. The self-initiated starts appeared to be an exception in that trunk muscle activity prior to the onset of movement was specific with respect to the direction of the impending perturbation.

Because of this preparation in anticipation of a predictable perturbation, limited trunk motion after the perturbation would be expected compared to the same, but unpredictable, perturbation. However, the changes in trunk orientation after the unpredictable perturbations did not exceed the changes after the predictable perturbations. At the same time, trunk muscle responses were different. After the unpredictable perturbation a higher level of trunk muscle activity was observed, and given the equal change in trunk orientation these responses would appear to be adequate to limit trunk motion in spite of the lack of anticipatory activation or pre-activation. Overall, changes in the EMG amplitudes were not different between agonists and antagonists. This suggests
that antagonistic muscle pairs were co-activated to increase trunk stiffness in response to the perturbations [30, 33, 129].

Although the magnitude of trunk motion was not affected by the predictability of the perturbations, it might differ between perturbations that are self-generated or externally generated. Taking as an example, the sudden stops, self-induced or externally induced described in chapter 3, similar trunk motions were observed in the both conditions. However, when the cart was stopped by the subjects themselves, trunk extension movement coincided with an internal extensor moment. In contrast, in the externally induced stop, trunk extension coincided with an internal flexor moment. This suggests that the trunk extension movement was actively controlled in the self-generated perturbation, while the externally generated perturbation may have caused a loss of control over trunk motion. Similarly, involuntary trunk inclination was observed after a sudden onset of cart movement (chapter 2), even when the perturbation was expected, possibly because its timing could not be predicted. These findings suggest that in cart pushing, trunk stiffness is generally too low to handle externally generated perturbations, in particular when they are unpredictable.

In summary, predictability of upcoming perturbations leads to an aspecific increase in trunk muscle activity before the perturbation resulting in higher trunk stiffness. In case of unpredictable perturbations, the response in muscle activity is not completely successful in preventing displacement of the trunk after the perturbation. Self-generated and externally generated perturbations induce similar magnitudes of trunk displacement, with different underlying kinetics.

**Effects of handle height on the trunk response to perturbations**

Handle height determines the magnitude of trunk inclination, which is larger when pushing at lower handle heights [48, 72, 110]. Consistent results on the effects of handle height were observed in the studies of the present thesis. When pushing at hip height, trunk inclination was larger than when pushing at shoulder height. The question was whether these differences in trunk position, as determined by handle height, affect trunk muscle control in response to
perturbations and more specifically, the range in trunk motion after the perturbation.

High postural activity of back muscle is generally associated with increased trunk inclination [101], which was confirmed by our finding of higher baseline EMG values in pushing at hip height than at shoulder height. In more controlled sudden release experiments higher pre-activation was shown to increase trunk stiffness [8, 30, 58, 118, 130,131]. Therefore, the trunk stiffness is probably relatively low when pushing at shoulder height, which would imply that the impact of the perturbation is different between pushing at shoulder height and pushing at hip height, as was indeed reflected in larger change in trunk inclination when pushing at shoulder height after the sudden start of cart movement (chapter 2). Similarly, the sudden stop perturbations, which occurred in a slightly forward inclined posture during pushing at shoulder height, caused trunk extension, which exceeded the neutral upright posture in four subjects, such that gravity could further destabilize trunk posture in the extension direction (chapter 3). The range of trunk motion in the transverse plane was also affected by the degree of trunk inclination in the sagittal plane. The larger trunk inclination when pushing at hip height limited the range of trunk twisting motion due to transverse planes perturbations (chapter 4 & chapter 5).

In summary, handle height in cart pushing, through differences in trunk inclination and differences in postural activity of the trunk muscles, affects the responses in trunk muscle activity and trunk motion after a perturbation. Compared to pushing at shoulder height, pushing at hip height provides higher trunk stiffness before the perturbation and reduces the impact of the perturbations by limiting trunk motion after the perturbation.

**Do perturbations in pushing tasks present a risk of injury to the low-back?**

From an epidemiological point of view, the relationship between pushing (and pulling) and the risk of low-back pain (LBP) is inconsistent [4, 21, 37, 38, 49, 94]. This may be due to the low demands associated with low spinal loads in pushing tasks [47]. Although the experiments in this thesis only evaluated pushing tasks, pulling forces are involved in the end phase of the pushing tasks,
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as mentioned in the general introduction (chapter 1) and have been considered as one of the important predictors of new-onset low-back pain [38]. The associated hand forces can act as a perturbation of the trunk, for instance in a self-induced stop (chapter 3) and in steering the cart (chapter 5). The perturbations studied in this thesis may be rare events at the workplace. Hence, it is very difficult to systematically record such exposures at the workplace and establish a direct relationship with low-back injury in an epidemiological study. This may explain why there is no direct epidemiological evidence linking perturbations in pushing tasks to low-back injury.

Based on the findings of the studies in this thesis, two potential risk factors in cart pushing can be identified, i.e. unpredictable externally generated perturbation and pushing at shoulder height, or most likely their interaction. When perturbations were unpredictable and externally generated, uncontrolled trunk motions appeared to occur. Such uncontrolled motions combined with forceful muscular responses may be a cause of injury [75]. Trunk stiffness was lowest when pushing at shoulder height, which was reflected by larger trunk motions after the perturbations compared to pushing at hip height. This indicates that trunk stability was endangered after the perturbation in cart pushing. The slow responses in the present study compared with the trunk muscle reflexes in response to unpredictable perturbations that were directly applied to the trunk [18, 34, 35, 118], may indicate that voluntary responses are involved [79]. The absence of fast feedback responses may prolong the period of trunk instability and increase the potential risk of low-back injury.

In summary, involuntary trunk motion with relatively long delays in trunk muscle activity after perturbations in cart pushing reflects that the state of the trunk could become unstable. In particular, unpredictable externally generated perturbations while pushing at shoulder height may present an injury risk. Anticipation and pushing at hip height increases trunk stiffness before the perturbation and reduce the impact of the perturbation and may protect the trunk against acute injury.
Factors affect pushing task demands

In cart pushing, cart weight is an important determinant of the task demand [24, 55, 74]. In the experiments described in this thesis, the cart weight was fixed at 200 kg, except for chapter 4 in which the pushing forces were set at 75 N and 150 N using a pulley system to represent cart weight s of approximate 200 and 400 kg cart. Overall, pushing forces observed in these studies were in the range of what has been observed in practice [46]. As mentioned in the general introduction (chapter 1), hand forces determine the trunk moment around L5S1 and consequently trunk loading is associated with cart weight in pushing [47, 48, 72]. When carts of higher weight are pushed using the same trunk inclination before a perturbation, higher trunk moments with higher trunk muscle activity are expected to limit perturbation impact [8, 30, 58, 118, 130, 131]. Alternatively, subjects may, however, increase inclination of whole body, using their body mass to produce higher hand forces. Therefore, changes in trunk muscle activity with cart weight are difficult to predict and care should be taken when generalizing the present results to other cart weights.

The purpose of pushing tasks is to transport objects, commonly objects with a large mass, from one place to another. This points at another way in which cart mass may affect task demands, i.e. when decelerating or accelerating a cart. Taking the sudden stop of the cart (chapter 3) as an example, a large hand force was used to decelerate the cart in order to stop as fast as possible when walking at self-selected speed. An increase in cart mass but also in speed would require even larger hand forces to decelerate the cart. The magnitude of changes in trunk muscle activity, moment and motion could be expected to be positively correlated with cart mass and speed. Steering a cart to turn, not only requires a linear deceleration but also a change in angular momentum. Two different ways of performing this task may be observed; subjects may exert a large backward force to stop prior to turning and this may be the more likely strategy when pushing a cart at high speed. Alternatively, subjects may directly exert a sideward force to turn without decelerating the cart and this may be the more likely strategy when pushing a cart at low speed. The choice of strategy will affect reaction forces at the hands and subsequently affect trunk moments.
around the lumbar spine and trunk muscle control, which should be considered with care when generalizing to other cart masses and speeds.

One could argue that, cart speed may be negatively associated with cart mass. However, in industry this tendency may be overruled by the efficiency requirements. In this case, although an increase in trunk stiffness due to the larger muscular effort for pushing the heavier cart is expected, once the perturbation occurs the large mass in combination with a large deceleration may result in larger perturbations. For steering a cart into a new travel direction, effects of the interaction between cart weight and cart speed task performance may be more complicated than for pushing in the straight line. Finally, people with experience may use different strategy to perform pushing tasks compared to college students participating in the present studies, which would coincide with different trunk motion and muscle activity [72], and which may consequently affect trunk muscle control in response to the perturbations.

In summary, this thesis was limited to studying young adults without experience in manual material handling activities pushing a 200 kg cart at self-selected walking speed. Cart weight and cart speed and their interaction will modify the external forces in pushing tasks and skilled workers may perform the tasks and handle the perturbations differently from the inexperienced subjects who participated in the experiments.

Comparisons with artificial perturbations

The studies in this thesis simulated realistic occupational pushing in the laboratory, except for chapter 2 in which pushing while walking on the treadmill was studied. To our knowledge, the experiments in this thesis are the first studies to evaluate effects of perturbations in cart pushing on trunk control. Pushing tasks are complex activities. Particularly, during dynamic pushing, the upper body is constrained by the handles of the cart and the lower body is moving cyclically, which puts the trunk in an awkward position. The trunk needs to provide sufficient stiffness to allow the upper extremities to control the cart. At the same time, walking challenges the dynamic equilibrium of the trunk and requires individuals to make appropriate adjustments [88].
Because of the absence of scientific literature on perturbations in pushing tasks, one of the first aims (chapter 2) was to determine whether previous findings from more controlled sudden release experiments [17, 18] could be generalized to realistic pushing tasks. The same pattern of reciprocal muscle activity (agonists switching off and antagonists switching on) indicates that a sudden drop in hand force is comparable to a sudden unloading perturbation of the trunk. However, a longer latency between the onset of the perturbation and the response of the trunk muscles was observed in pushing tasks. This might because of the slower drop in the external moment in pushing compared to the artificial perturbations [17]. The impact of the perturbation to the trunk may be determined by the rate of change in the external moment, which makes it difficult to compare pushing tasks and artificial perturbations. Velocity-related feedback, providing damping of the perturbation can be mediated through fast monosynaptic spindle feedback [18, 101, 103]. However, in the present thesis latencies, in EMG responses were longer than 120 ms, which indicates that these may be voluntary responses [79]. While it could be argued that this is due to the fact that perturbations were taking effect through the upper extremities in the pushing tasks, the observed latency was also long compared to those after sudden pulls on the wrist while standing [42]. Therefore, it appears more likely that this difference is due to the rate of change in the external moment.

A clear difference between artificial perturbations used in previous experiments and realistic perturbations during pushing tasks is that artificial perturbations were unidirectional, while the changes in hand forces in cart pushing are multidirectional. Specifically, when making a turn (chapter 5), the trunk needs to manage not only the moment in the sagittal plane produced by the horizontal and vertical components of the reaction forces at the hands, but also the moments in the transverse plane produced by the horizontal and the sideward components of reaction forces. Additionally, the reaction forces were asymmetrical between left and right hands. Trunk muscle control needs to deal with these multi-plane perturbations to the trunk at the same time. This suggests that the findings on trunk muscle control in handling artificial perturbations cannot be completely generalized to realistic tasks and may underestimate the effort required to control the trunk [111].
Chapter 6

Pushing tasks are not only occupational activities, but also common in daily life, such as pushing a shopping cart when walking around the supermarket. In this thesis, we used cart pushing to simulate sudden force changes at the hands to perturb the trunk. These perturbations could also occur in other tasks in daily life. For instance, when opening a door while someone on the other side of the door opens the door at the same time (chapter 2) or when walking a dog that suddenly runs away or stops (chapter 3, chapter 4 and chapter 5). These situations all involve sudden and/or unexpected multi-directional force changes at the hands that may occur while walking, and these examples illustrate the differences between daily activities and artificial perturbations.

In summary, sudden force changes at hands can be considered as perturbations to the trunk. The same pattern of trunk muscle activity, but with different onset timing and magnitude, indicates that findings of artificial perturbation experiments cannot completely be generalized to the functional pushing tasks of this thesis and may underestimate the risk of low-back injury. Perturbations will usually not be constrained to one anatomical plane and may occur in trunk and upper extremity positions, in other words in daily life the trunk is not only handling unidirectional perturbations in an upright posture. In order to answer how the trunk does maintain stability and handles the multidirectional trunk perturbations, further research is needed.

Future research

As mentioned above, there are important differences between perturbations in realistic (pushing) activities and artificial perturbations with respect to the direction and point of application of the perturbation. Recent studies suggest that multidirectional moments are quite challenging for trunk muscle control [87, 111, 119]. Additionally, the same magnitude perturbation (external moment) may induce larger trunk muscle activity when imposed through the hands compared to via a trunk harness [85]. Therefore, for future research, we would like to gain more knowledge concerning the differences and similarities in trunk muscle control in response to multidirectional perturbations applied directly to the trunk and applied at the hands. Furthermore, with respect to the perturbations at the hands in terms of simulations of realistic activities,
Epilogue

the functional positions of the upper extremities may affect the rate of change in the external moment and be an important factor to consider when investigating the effects on trunk muscle control. Performing functional tasks while walking is not only multitasking for the CNS, which needs to control fine motor and gross motor actions simultaneously, but also puts the trunk in an awkward position to provide stiffness and online equilibrium adjustments at the same time. In this case, sudden unpredictable perturbations may well approach the limits of the capacity and adaptability of trunk control. Finally, therefore perturbation experiments need to address such dynamic situations to provide insight in trunk control in realistic activities.
Chapter 6

Conclusion

This thesis provides some insight into the effects of perturbations at the hands on trunk muscle control and trunk motion by evaluating cart-pushing tasks. The main objective of this thesis was to study the control of the trunk in response to predictable and unpredictable perturbations that were self-generated or externally generated during pushing a cart with the handles at shoulder and hip height. Based on the findings of the four experiments studied in this thesis, it can be concluded that changes in hand forces coinciding with changes in the velocity of the cart cause perturbations of the trunk. Preparatory cocontraction of trunk muscles served to increase trunk stiffness in anticipation of changes in cart movement (chapter 2 & 5). However, this increased trunk stiffness was not completely successful in preventing increased trunk motion in the lumbar spine (chapter 2, 4 & 5). Additionally, the findings show that appropriate muscle control caused voluntary trunk motion in self-generated perturbations, while externally generated perturbations caused uncontrolled trunk motion (chapter 3). Pushing at shoulder height may impose a higher risk of low-back injury than pushing at hip height due to the lower trunk stiffness and larger trunk motion. Consequently, it may be preferable to push objects at hip height. This thesis also points out differences between artificial perturbations and perturbations during realistic functional activity. Future research studying the effects of multidirectional perturbations imposed at hands can contribute to fundamental knowledge about how the CNS controls the trunk to deal with perturbations during daily activities.
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Summary

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摘要
Control of trunk movement: Perturbations in cart pushing

Mechanical perturbations challenge trunk stability, which is considered a risk factor for low-back injury. Increased trunk muscle activity causes an increase in trunk stiffness, which enhances the trunk stability and may thus prevent negative effects of mechanical perturbations. However, trunk stiffness is relatively low during low-demand tasks, such as pushing tasks. Pushing carts has therefore been suggested to impose a challenge for trunk muscle control as a system with a relatively low stiffness may have to deal with perturbations induced by an object with high inertia. This might cause uncontrolled trunk motions and inappropriate trunk muscle responses could further increase the risk of low-back injury.

In pushing tasks, handle height is one of ergonomic factors, which determines trunk posture and affects trunk muscle activity, i.e. when pushing at low handle height trunk inclination is larger and trunk muscle activity is higher, which may affect the impact of perturbations. In addition, expectation of an impending perturbation may lead to early initiation of trunk muscle activity, which may also reduce the impact of the perturbations. This thesis focuses on trunk moment perturbations in the sagittal plane and transverse planes in combination with corresponding trunk muscle activity in response to perturbations, which can occur when pushing a cart. The principal objectives of the studies were: (1) to study the effects of predictable perturbations on the control of trunk muscle activity and trunk motion before the actual occurrence of the perturbations, (2) to study the effects of predictable and unpredictable perturbations on the control of trunk muscle activity and trunk motion after the occurrence of the perturbations, and (3) to study the effects of self-generated and externally generated perturbations on trunk motion after the occurrence of the perturbations and, finally, (4) to study differences in trunk muscle control and trunk motion in response to the perturbations when pushing at shoulder height or hip height.

In chapter 2, we studied the effects of handle height and the expectation of sudden unloading during the transition of cart movement from static to dynamic friction. Subjects were asked to push a cart with brakes (externally triggered) and without brakes (self-initiated). This sudden drop in contact force at the hands associated with the onset of cart movement is considered as a sudden
unloading perturbation. Compared to pushing at hip height, lower muscle activity and trunk stiffness at shoulder height before onset resulted in a higher trunk inclination after onset. Before self-initiated cart movement, trunk stiffness and muscle activity were significantly higher than before an externally triggered onset at a comparable pushing force. 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.

Change in contact force at the hands was shown to cause a perturbation of the trunk in the previous chapter. Opposite to the sudden unloading perturbation in cart pushing, sudden loading was studied in chapter 3. The objective of this study was to investigate whether different types (self-generated & externally generated) of sudden loading perturbations due to sudden stops while pushing a high inertia cart. Subjects were instructed to stop a cart as fast as possible after an auditory cue (self-induced stop) or the wheels of the cart were unexpectedly blocked (externally induced stop). Initial responses in both stops consisted of flexor and extensor muscle cocontraction. In the self-induced stops, trunk extension coincided with an internal extensor moment, indicating that voluntary trunk extension was observed. In the externally induced stops, an external extension moment caused a decrease in trunk inclination. The opposite directions of the internal moment and trunk motion in the externally induced stop while pushing at shoulder height may indicate loss of control over trunk posture. In conclusion, different types of perturbations in cart pushing induce voluntary (self-generated) and involuntary (externally generated) trunk motions and particularly when pushing at shoulder height externally generated perturbations may put the low back at risk of mechanical injury.

The horizontal component of the hand force in pushing also affects trunk moments in the transverse plane, i.e. the trunk twisting moments around the L5S1 joint. These moments were expected to vary cyclically when pushing while walking and the objective of chapter 4 was to investigate whether cyclic oblique abdominal muscle activity was associated with cyclic pushing forces when pushing while walking. In addition, we hypothesized that external and unpredictable perturbations would be counteracted by cocontraction of the
Control of trunk movement: Perturbations in cart pushing

oblique abdominal muscles. Subjects were instructed to push at two target forces in a static standing position, while walking and additionally while walking and pushing against a randomly perturbed target force to simulate the effect of non-constant rolling resistance. A tonic level of oblique abdominal muscle activity (static component of EMG amplitudes) was used to maintain trunk posture in pushing while walking. The additional dynamic activity was associated with the twisting moments, which were actively modulated by the pairs of oblique muscles as in normal gait. In line with the hypothesis, in the perturbed condition, an increased baseline of oblique abdominal muscle activity reflected cocontraction of the antagonistic muscle pairs of trunk rotator muscles, which was associated with an increase in trunk stiffness around the longitudinal axis.

The small asymmetry of the hand reaction forces in pushing while walking studied in chapter 4 elicited trunk oblique abdominal muscle cocontraction. More asymmetry of the hand forces is expected when steering a cart to make a turn. The objective of chapter 5 was to investigate effects of the predictability of the perturbation induced by making a turn while pushing. Subjects were instructed to push while making a gradual turn, a sharp turn and an unexpected sharp turn (i.e. making a sharp turn as fast as possible after an auditory cue). An increase of oblique abdominal muscle activity before the gradual and sharp turns indicated that anticipatory activation occurred when a turn was planned, which was however not directionally specific. After a left turn, trunk twisting motion to the right was associated with a twisting moment in the same direction induced by the reaction forces on the left hand and presumably slowed down by an increased stiffness as a consequence of the bilateral oblique abdominal muscle activity. Anticipatory activation was absent in the unexpected sharp turns and bilateral trunk rotator muscle activity increased only after the turn. Trunk rotation to the right was faster than in the planned turns. In conclusion, trunk motion in pushing while turning was initially opposite to the travel direction. Additionally, the predictability of the turn affected the control of this trunk twisting motion. In the unexpected turns, the combination of an uncontrolled twisting motion with delayed muscle activation may increase the potential risk of low-back injury.
Summary

In conclusion, this thesis provides evidences of changes in contact force at the hands in pushing being a perturbation to the trunk that 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 increased trunk stiffness, but did not completely prevent displacements of the trunk. The impact of perturbations in pushing was attenuated by the increase in trunk inclination associated with pushing at hip height. When generalizing the findings of this thesis to other situations, such as a different cart mass, cart speed or population, the responses of trunk muscle activity and motion should be considered with care, as these factors may affect task demands in terms of external moments to the trunk. Previous studies on trunk control mainly addressed unidirectional sudden loading or sudden release perturbations applied directly to the trunk. In functional activities, perturbations may be multidirectional and may be applied either directly at the trunk or at the hands. The studies presented highlighted differences in patterns of trunk muscle activity between artificial perturbations used in previous studies on trunk control and realistic perturbations during functional activities.
Controle van rompbewegingen bij verstoringen tijdens het duwen van karren

Het mechanisch verstoren van de romp wordt gezien als een risicofactor voor lage rugklachten. Dergelijke verstoringen kunnen zorgen voor ongecontroleerde bewegingen van de romp waarbij een inadequate reactie van de romspieren het risico op lage rugklachten verder kan vergroten. Het verhogen van de activiteit van de romspieren zorgt voor een toename in de stijfheid van de romp waarmee negatieve effecten van verstoringen kunnen worden voorkomen. Bij activiteiten met relatief geringe fysieke eisen met betrekking tot rugbelasting, zoals het duwen van karren, is ook de stijfheid van de romp relatief laag, terwijl de kar door zijn hoge inertie grote verstoringen kan veroorzaken. Het duwen van een kar wordt daarom ook gezien als een activiteit waarbij de controle van de romspieren belangrijk is om verstoringen van de romp te kunnen weerstaan.

Tijdens duwactiviteiten is de aangrijphoogte van de handen bepalend voor de houding van de romp en de activiteit van de romspieren. Tijdens het duwen met een lage aangrijphoogte is de romp meer voorover gebogen en is de activiteit van de romspieren hoger. Dit zou het effect van verstoringen tijdens het duwen kunnen beïnvloeden. Ook is het wel of niet verwachten of voorspellen van een mogelijke verstoring van belang. Als een verstoring wordt verwacht is het mogelijk dat de romspieren al actief zijn voordat de verstoring plaats vindt, hetgeen ook het effect van de verstoring kan beïnvloeden. Dit proefschrift richt zich op verstoringen van het moment op de lage rug in sagittale en transversale richtingen en de activiteit van de romspieren die daarmee samengaat tijdens het duwen van een kar. De centrale onderzoeksvragen zijn: 1) Wat is het effect van voorspelbare verstoring tijdens het duwen van een kar op de controle van de activiteit van romspieren en de bewegingen van de romp vlak na de verstoring? 2) Wat zijn de verschillen tussen voorspelbare en onvoorspelbare verstoringen tijdens het duwen van een kar met betrekking tot de controle van de activiteit van romspieren en de bewegingen van de romp vlak na de verstoring? 3) Wat zijn de effecten van zelf-gegenereerde en extern-gegenereerde verstoringen tijdens het duwen van een kar op de controle van de bewegingen van de romp vlak na de verstoring? 4) Wat zijn de verschillen in de controle van de activiteit van romspieren en de bewegingen van de romp als reactie op verstoringen
tussen het duwen van een kar met de handen op schouderhoogte en op heuphoogte.

**Hoofdstuk 2** behandelt de effecten van aangrijphoogte en voorspelbaarheid bij het plotseling vanuit stilstand gaan rijden van een kar tijdens duwen in een laboratorium experiment. De deelnemers aan het experiment duwden tegen een kar met door remmen geblokkeerde wielen waarna de proefleider op een onverwacht moment de remmen ontkoppelde en de kar ging rijden (extern-gegeneerderde verstoring). Daarnaast duwden de deelnemers ook vanuit stilstand tegen een kar zonder remmen (zelf-gegeneerderde verstoring). Wanneer de kar gaat rijden worden de geleverde handkrachten plotseling kleiner, wat wordt gezien als plotselinge, rugbelasting verlaging, verstoring. De lagere spieractiviteit en lagere stijfheid van de romp bij het duwen op schouderhoogte in vergelijking met het duwen op heuphoogte vlak voor het gaan rijden van de kar resulteerde in het meer voorover buigen van de romp bij het gaan rijden van de kar. Bij een vergelijkbare duwkracht blijken de activiteit van de romspieren en de stijfheid van de romp significant hoger te zijn vlak voor de zelf-gegeneerderde verstoring in vergelijking met de extern-gegeneerde verstoring. Geconcludeerd wordt dat de waargenomen, hogere, voorbereidende activatie van de romspieren de stijfheid van de romp verhoogt ter voorbereiding op het gaan rijden van de kar en zorgt dat het effect van de – met het gaan rijden van de kar gepaard gaande – verstoring wordt verminderd.

Het vorige hoofdstuk liet een verstoring van de romp zien bij een plotseling verandering in grootte van de handkrachten. Naast deze plotselinge, rugbelasting verlaging, verstoring bij het duwen van een kar, is in **hoofdstuk 3** de plotselinge, rugbelasting verhogende, verstoring bestudeerd. Het doel van deze studie was het onderzoeken van de verschillen tussen zelf-gegeneerderde en extern-gegeneerderde verstoringen met een rugbelasting verhogend effect als gevolg van het plotseling stoppen met duwen van een kar met een hoge inertie. De deelnemers aan het experiment moesten, terwijl ze een rijdende kar aan het duwen waren, zo snel mogelijk de kar stoppen na het horen van “stop!” (zelf-gegeneerderde stop). Deze situatie werd vergeleken met de situatie waarbij de kar zelf stopte met rijden door het botsen tegen een obstakel (extern-gegeneerderde stop). Als reactie op de verstoring werd bij beide situaties co-contractie van
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rompflexoren en rompextensoren waargenomen. Bij de zelf-gegenereerde stop ging extensie van de rug samen met een intern extenderend moment, hetgeen wijst op een vrijwillige extensie van de rug. Bij de extern-gegenereerde stop werd een extern extenderend moment waargenomen hetgeen resulteerde in een afname van rompflexie. De tegengestelde richtingen van het interne moment en de beweging van de romp bij de extern-gegenereerde stop bij het duwen op schouderhoogte zou kunnen wijzen op het verliezen van de controle over de houding van de romp. Concluderend kunnen verschillende vormen van verstoringen bij het duwen van karren vrijwillige (zelf-gegenereerde) en niet-vrijwillige (extern-gegenereerde) bewegingen van de romp als gevolg hebben. Met name bij het duwen van een kar op schouderhoogte kunnen extern-gegenereerde verstoringen het risico op mechanische schade aan de lage rug vergroten.

De horizontale component van de geleverde handkrachten bij het duwen van een kar is ook van invloed op de momenten op de lage rug in het transversale vlak, dat wil zeggen de momenten die voor de rotatie van de romp zorgen. Een cyclisch patroon van deze momenten is te verwachten wanneer een persoon loopt en tegelijkertijd een rijdende kar duwt. Het doel van hoofdstuk 4 was om te onderzoeken of het cyclisch activeren van de rotatoren van de romp (m. obliquus externus abdominis en internus abdominis) geassocieerd is met het cyclische patroon van de geleverde duwkrachten van de handen tijdens het lopend duwen van een kar. De hypothese was dat externe en onvoorspelbare verstoringen worden opgevangen door middel van co-contractie van de rotatoren van de romp. Tijdens de experimenten duwden deelnemers tegen een kar op een lopende band met twee niveaus van handkrachten onder drie condities: 1) stilstaand, 2) lopend, en 3) lopend terwijl de handkrachten random verstoord werden. Bij het lopend duwen werd de houding van de romp vastgehouden met een statische component van de spieractiviteit van de rotatoren van de romp. Op de statische component was een dynamische component zichtbaar die overeenkwam met de rotatoire momenten op de lage rug. Deze rotatoire momenten werden actief gegenereerd door de paren van de rotatoren van de romp zoals ook bij normaal lopen te zien is. In overeenstemming met de hypothese gaf in de verstorende conditie het
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verhoogde basis niveau van de activiteit van de rotatoren aan dat er sprake was van co-contractie van de antagonistische paren van de rotatoren, hetgeen samen ging met een toename in de stijfheid van de romp rond de longitudinale as.

Het asymmetrische en cyclische patroon van de geleverde handkrachten tijdens het lopend duwen, zoals bestudeerd in hoofdstuk 4, bleek samen te gaan met co-contractie van de rotatoren van de romp. Meer uitgesproken asimetrie in de handkrachten kan verwacht worden bij het nemen van een bocht tijdens het duwen van een kar. In hoofdstuk 5 is het effect van de voorspelbaarheid van de verstoring door het nemen van een bocht bij het lopend duwen van een kar onderzocht. In een laboratorium experiment moesten deelnemers lopend een kar duwen en vervolgens 1) een ruime bocht nemen, 2) een scherpe bocht nemen en 3) een scherpe onverwachte bocht nemen zo snel mogelijk na het horen van “turn!”. Vlak voor het nemen van de ruime en scherpe bocht was de activiteit van de rotatoren van de romp verhoogd. Dit duidt er op dat er bij de aansturing van deze spieren wordt geanticipeerd op het nemen van een geplande bocht. De aansturing was echter niet specifiek voor de richting van de benodigde rompbeweging. Vlak na het inzetten van de bocht naar links werd een rotatoire beweging van de romp naar rechts waargenomen die samenging met een rotatoir moment op de lage rug in dezelfde richting. Dit moment werd veroorzaakt door de reactiekrachten op de linker hand en werd waarschijnlijk geremd door een toegenomen stijfheid van de romp als gevolg van de waargenomen activiteit van antagonistische rotatoren van de romp. Bij het nemen van een scherpe onverwachte bocht werd geen anticiperende activatie van de rotatoren waargenomen en de activiteit van de rotatoren nam alleen na het inzetten van de bocht toe. Daarnaast was bij het nemen van een scherpe onverwachte bocht de rotatie van de romp naar rechts sneller dan bij het nemen van de geplande bochten. Er wordt geconcludeerd dat bij het inzetten van een bocht bij het lopend duwen van een kar de romp in een richting roteert die tegengesteld is aan de draairichting van de kar. Daarnaast beïnvloedde de voorspelbaarheid van het nemen van de bocht de controle van deze romprotatie. Bij het onverwacht moeten nemen van een bocht bij het lopend duwen van een kar kan de combinatie van een ongecontroleerde roterende beweging van de
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romp met een vertraging in de activatie van de rotatoren van romp het potentiele risico op schade aan de lage rug verhogen.

Uit de studies beschreven in dit proefschrift kan geconcludeerd worden dat – plotseling – veranderingen in de geleverde handkrachten bij het duwen van een kar, hetzij zelf-gegeneereerd, hetzij extern-gegeneereerd, als een verstoring voor de romp en daarom als een risico voor schade aan de lage rug gezien kunnen worden. Bij het duwen van karren, met name bij het duwen met de handen op schouderhoogte, kunnen extern-gegeneereerde onvoorspelbare verstoringen ongecontroleerde bewegingen van de romp tot stand brengen waarbij reacties in spieractiviteit relatief laat optreden. Anticiperend op voorspelbare en zelf-gegeneereerde verstoringen wordt de stijfheid van de romp verhoogd door een toename in activiteit van de rompspieren, maar dit kan de bewegingen van de romp door de veranderende handkrachten niet geheel voorkomen. Het effect van verstoringen bij het duwen van een kar kan worden beperkt door het meer voorover buigen van de romp, zoals bij het duwen van een kar op heuphoogte. Voorzichtigheid is geboden bij het generaliseren van de resultaten uit dit proefschrift naar andere situaties waarbij een kar wordt geduwd, bijvoorbeeld bij andere kargewichten, loopsnelheden en populaties. Dergelijke factoren beïnvloeden de taak-eisen in termen van momenten op de lage rug en dus ook de reacties in activiteit van de rompspieren en beweging van de romp. Eerdere onderzoeken met betrekking tot motorische sturing van de romp gingen met name over het onverwacht belasten van de romp in één richting, bijvoorbeeld alleen voor- of achterwaarts, of over verstoringen direct aangrijpend op de romp waarbij de belasting juist onverwacht werd verwijderd. Bij dagelijkse activiteiten of werkzaamheden kunnen verstoringen echter meerdere richtingen beïnvloeden, bijvoorbeeld zowel voor- als zijwaarts, en kunnen deze direct op de romp maar ook op de handen aangrijpen. In het proefschrift worden tenslotte de verschillen in motorische sturing van romp tussen opgelegde verstoringen in experimentele situaties en verstoringen die kunnen voorkomen bij het uitvoeren van dagelijkse activiteiten of werkzaamheden bediscussieerd.
Samenvatting
駕駛動作控制：推車任務中的干擾

對駕駛穩定性(trunk stability)而言，機械性干擾(mechanical perturbation)可視為下背傷害的危險因子之一。駕駛肌肉活動增加同時増強的駕駛硬度(stiffness)可進而增加駕駛的穩定性，或許可預防機械性干擾所帶來的負面影響。然而，當執行較低需求(low-demand)的任務時，駕駛的穩定性相對來說也較低；挿例來說：推車任務。在執行推進推車這項任務時，駕駛本身的相對穩定性低，卻需要同時面對物體處於高慣性時所伴隨的干擾。因此，雖然駕駛本身的需求較低，但卻挑戰了駕駛肌肉控制的能力。除此之外，有可能造成不自主駕駛動作和引起不適當駕駛肌肉活動反應，因而進一步提高下背傷害的危險。

握把高度是影響推車任務的人因工程因子之一，其決定駕駛姿勢和影響駕駛肌肉活動；當握把高度較低時，駕駛往後傾斜角度和肌肉活動較大，此現象有可能會影響在執行任務時，機械性干擾對駕駛所帶來的衝擊程度。再者，對於即將發生的干擾有某種預期時，有可能導致駕駛肌肉提早起始活動而降低干擾對駕駛的衝擊。本論文將著重於駕駛力矩在矢狀面和橫狀面的干擾和其相對應駕駛肌肉對於不同種類的干擾發生在推進推車時的肌肉活動變化。主要研究目的為：(1)研究駕駛肌肉活動控制和駕駛動作在實際干擾發生前，當干擾可預測時所造成的影響；(2)研究當干擾為可預測或不可預測時，對駕駛肌肉活動控制和駕駛動作在實際干擾發生後的影響；(3)研究當受試者自身引起(self-generated)干擾或是外在產生(externally generated)干擾，對駕駛動作在實際干擾發生後的影響；最後，(4)研究執行推進任務於握把處於肩關節高度或髖關節高度時，駕駛肌肉控制和駕駛動作應變干擾發生時的差異。

在第二章的研究中，我們研究握把高度和預期性對推車狀態克服靜摩擦力轉換為動摩擦力造成瞬間負荷卸載(unloading)干擾的影響。受試者被指示推動一煞車煞住的推車(此為外在產生干擾情況)和同一推車但沒有煞住煞車(此為受試者自身引起干擾情況)。手的接觸力突然下降與推車移動相關連可被視為瞬間負荷卸載的干擾。從握把高度因素來探討干擾的影響，當握把高度為肩關節高度時，駕駛肌肉活動和駕駛硬度在推車移動發生前較握把於髖關節高度時低，因而造成在推車移動發生後，產生較大的駕駛傾斜角度。另一方面，從受試者自身引起干擾或是外在產生干擾的角度來比較，在受試者自身引起干擾情況下，駕駛硬度和肌肉活動在推車移動前顯著高於相似推進力施於外在產生干擾情況。
對於預期推車即將移動而起始脢幹肌肉準備性活動(preparatory activation)來提供脢幹增強硬度，也許可降低推車移動瞬間所產生對脢幹千擾的衝擊。

前一章提出當雙手接觸力改變時，會對脢幹造成千擾。與瞬間負荷卸載千擾相對的瞬間加重負荷將於第三章進行研究。此研究目的在探討當推車處於高慣性狀態時，不同方式(受試者自身產生或是外在產生)突然急停行進中推車所引起的瞬間加重負荷千擾對脢幹的影響。在執行推進任務過程中，受試者被指示當聽到聲音指令(stop)時，儘快停車，此為受試者自身產生千擾情況。不同於受試者自行停車，任務執行過程中，車輪會不預期的被障礙物卡住而造成行進中的推車立即停止，此為外在產生千擾情況。在兩種情況下，脢幹屈肌和伸肌的初始反應皆為共同收縮。然而，在受試者自身產生千擾情況下，千擾產生後，脢幹動作為伸展方向與內在屈肌力矩增加行為相符，此結果顯示脢幹伸展動作為自主性動作。反之，在外在產生千擾情況下，外在伸展力矩卻導致減少脢幹傾斜角度。換言之，相對應的內在屈肌力矩並無引起增加脢幹傾斜角度應有的作用。當推進推車於肩關節高度因外在環境造成推車瞬間停駛的情況，內在力矩與脢幹動作呈現相反方向或許指出脢幹姿勢在千擾時失去控制。在推進任務中，不同種類型的千擾會引起自主性(自身產生千擾)和非自主性(外在產生千擾)的脢幹動作，尤其是外在產生千擾發生在推進於肩關節高度時，此情境或許會令下背處於機械性傷害的危險情況。

在推進任務中，橫向推進力不僅影響脠狀面脢幹力矩，同時也影響脠狀面脢幹力矩，比如說：旋轉力矩於脣翼關節(L5S1 joint)周圍。當執行推進任務伴隨走路時，這些力矩被預期會隨著步態而有週期性的變化。因此，第四章的研究目的在探討動態推進任務中(推進伴隨走路)，週期性腹部斜狀肌(oblique abdominal muscle)的肌肉活動是否與週期性的推進力相關連。另外，我們假設當不可預測的外在干擾發生時，腹部斜狀肌肉群會共同收縮來抵抗此一干擾。受試者被指示在靜態站立姿勢、走路和走路同時附加額外干擾的三種情況下，分別推進兩個預設阻力目標。附加額外干擾的情況為隨機性干擾預設阻力目標以其來模擬當推車行進於滑動阻力不一致路面的效果。腹部斜狀肌的連續性放電肌肉活動程度(tonic level)定義為肌肉動作電位圖中的靜態構成元素，此部份肌肉活動用於維持在執行推進伴隨走路情況時的脢幹姿勢。而動態構成元素如
駕駛動作控制：推動任務中的干擾

同正常行駛一般，責任範圍在執行推進伴隨走狗情形時的駕桿旋轉力矩，並且由成對的腹部斜狀肌（同側腹外斜肌與對側腹內斜肌）自動調節控制。當執行附屬額外干擾情況時，腹部斜狀肌增加基本肌肉活動與假設相符，其反應駕桿旋轉肌群中相對拮抗肌的共同收縮，並且與增加駕桿縱軸周圍的硬度相關。

有些不對稱手部反作用力於動態推進任務已研究於在第四章，並發現此不對稱的手部反作用力會誘發駕桿斜狀肌的共同收縮。因此當需要操控推車改變方向時，預期會觀察到較大不對稱的推進力產生。第五章的研究目的為探討預測性對推車轉向所引起干擾的影響。受試者被要求推進推車並執行兩種不同的轉向方式，第一種命名為逐漸轉向(gradual turn)：將進進中的推車逐漸向左轉。

在逐漸轉向和區別轉向之間，腹部斜狀肌肉活動明顯增加。這結果表示當在執行有計劃性的要將推車轉向時，實際發生推車轉向之前，駕桿肌肉起始預期性活動(anticipatory activation)；然而，左右側肌肉群的肌肉活動並未對駕桿轉動方向顯示特定方向(directionally specific)的差異。在推車向左轉後，駕桿動作向右，此與左手反作用力所造成的旋轉力矩方向相同，不過，此駕桿動作有可能因兩側腹部斜狀肌肉活動因而增加的駕桿硬度而變緩慢。另外在執行不可預測尖銳轉向時，缺乏預期性肌肉活動，雙側腹部斜狀肌肉活動只在轉向實際發生後增加，並且駕桿向右轉動動作速度快於有計畫性轉向情況。合推車轉向過程中，初始的駕桿動作與推車動向呈現相反方向。具體來說，當推車向左轉時，初始的駕桿為向右轉的動作。再者，是否执行推車轉向的預測性影響駕桿旋轉動作的控制。更重要的是當執行不可預測尖銳轉向時，非自主駕桿旋轉動作伴隨延遲的駕桿肌肉活動也許會增加下背傷害的潜在危險。

總結，本論文提出證據顯示在執行推進任務時，改變雙手的接觸力對駕桿來說是種干擾，並且有可能加深下背傷害的危險。主要結論為當推進推車任務中不可預測且外在產生的干擾發生時，尤其是在推進於肩關節高度時，會導致非自主性的駕桿動作並引發較慢的肌肉活動反應來抵抗此種干擾。另一方面，可預測且受試者本身產生的干擾，在干擾發生前，預期性的肌肉活動增強了駕桿動作的影響。
摘要

幹的硬度，雖然在干擾發生之後並未完全阻止幹幹動作的變化。再者，由於推
進於髖關節高度所導致增加的幹幹傾斜角度可有效減弱推進過程中千擾所帶來
的衝擊。然而，將本論文的結果應用於其他，像是不同推車重量、推車速度或
是人口的狀況時，應特別注意。因為這些因素有可能會影響任務本身的需求，
換言之，施予幹幹上的外在力矩。早期對於幹幹控制的研究主要著重於單一方
向性的瞬間負荷卸載或是瞬間加重負荷干擾，並且將干擾直接施予幹幹本身。
然而在功能性活動上，干擾有可能是多方向同時產生的。此種干擾有可能直接
加諸於幹幹上或經由雙手而影響幹幹。最後，此博士論文研究呈現並強調幹幹
肌肉活動模式在早期研究幹幹控制的人造干擾上和功能性活動的實際干擾上兩
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能性活動中的控制機制。
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