

## Implications of increased medio-lateral trunk sway for ambulatory mechanics

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### Abstract

The purposes of this study was to test a mechanism to reduce the knee adduction moment by testing the hypothesis that increased medio-lateral trunk sway can reduce the knee adduction moment during ambulation in healthy subjects, and to examine the possibility that increasing medio-lateral trunk sway can produce similar potentially adverse secondary gait changes previously associated with reduced knee adduction moments in patients with knee osteoarthritis. Nineteen healthy adults performed walking trials with normal and increased medio-lateral trunk sway at a self-selected normal walking speed. Standard gait analysis was used to calculate three-dimensional lower extremity joint kinematics and kinetics. Knee and hip adduction moments were lower (−65.0% and −57.1%, respectively) for the increased medio-lateral trunk sway trials than for the normal trunk sway trials. Knee flexion angle at heel-strike was 3° higher for the increased than for the normal trunk sway trials. Knee and hip abduction moments were higher for the increased medio-lateral trunk sway trials, and none of the other variables differed between the two conditions. Walking with increased medio-lateral trunk sway substantially reduces the knee adduction moment during walking in healthy subjects without some of the adverse secondary effects such as increased axial loading rates at the major joints of the lower extremity. This result supports the potential of using gait retraining for walking with increased medio-lateral trunk sway as treatment for patients with degenerative joint disease such as medial compartment knee osteoarthritis.

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### 1. Introduction

The load distribution between the medial and lateral compartments of the knee during walking is critical for both healthy and osteoarthritic cartilage (Andriacchi et al., 2004). The distribution of loads transferred through the medial and lateral compartments during walking can be estimated by the external knee adduction moment (Schipplein and Andriacchi, 1991); a greater external knee adduction moment indicates greater loads in the medial than in the lateral compartment. The external adduction

moment at the knee during walking has been shown to be a strong predictor for the presence (Schnitzer et al., 1993; Baliunas et al., 2002; Gök et al., 2002), severity (Sharma et al., 1998; Mündermann et al., 2004) and rate of progression (Miyazaki et al., 2002) of medial compartment knee osteoarthritis.

Many interventions for knee osteoarthritis have the goal of reducing the external knee adduction moment during walking. These interventions range from non-invasive interventions such as bracing (Lindenfeld et al., 1997; Pollo et al., 2002), footwear modifications (Kerrigan et al., 2002, 2003; Fisher et al., 2007), gait training (Mündermann et al., 2004) and quadriceps muscle strengthening (Fisher et al., 1991, 1993; Røgind et al., 1998; Fransen et al., 2001; Huang et al., 2003) to highly invasive surgical interventions such as high tibial osteotomy (Prodromos et al., 1985).

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The knee adduction moment is in part determined by the line of action and the magnitude of the ground reaction force, while the foot is in contact with the ground. The ground reaction force is equal and opposite in direction to the force that the foot applies to the ground during contact. The medial-lateral component of the ground reaction force reflects the acceleration of the center of mass in the frontal plane, which is largely determined by the medio-lateral motion of the trunk due to its large relative mass (Hatzel, 1980). However, it is unknown whether increased medio-lateral trunk sway alone can cause altered lower extremity kinematics and kinetics during ambulation, similar to those observed in patients with medial compartment knee osteoarthritis.

It has recently been reported (Mündermann et al., 2005) that some patients with medial compartment knee osteoarthritis naturally adopt an altered gait pattern that reduces the knee adduction moment and is driven by a change in medio-lateral trunk sway. This gait pattern involved more extended knees at heel-strike, greater lateral ground reaction force, greater axial loading rates at the ankle, knee and hip, increased knee and hip abduction moments resulting in reduced knee and hip adduction moments. Changes in the axial loading rate at the ankle, knee, and hip may be harmful to cartilage. For instance, higher loading rates have been shown to generate more surface fissuring of cartilage than lower loading rates (Ewers et al., 2002), and surface fissures in the cartilage can propagate mechanically if the joint surface is subjected to rigorous repetitive loading (Kerin et al., 2003). Thus, increased loading rates may not only accelerate fibrillation of already damaged cartilage, as observed in severe knee osteoarthritis, but may also lead to the initiation of osteoarthritis at adjacent joints, including the hip.

The purpose of this study was to test a mechanism to reduce the knee adduction moment by testing the hypothesis that increased medio-lateral trunk sway can reduce the knee adduction moment during ambulation in healthy subjects. We also examined the possibility that increasing medio-lateral trunk sway can produce similar potentially adverse secondary gait changes previously associated with reduced knee adduction moments in patients with knee osteoarthritis. In particular, we tested the hypothesis that gait changes related to increased medio-lateral trunk sway in healthy subjects are associated with more extended knees at heel-strike, greater lateral ground reaction force, greater axial loading rates at the ankle, knee and hip, increased knee and hip abduction moments resulting in reduced knee and hip adduction moments compared with walking with normal trunk sway. This study included subjects with healthy joints, to account for the possibility that for patients with medial compartment knee osteoarthritis the effects of medio-lateral trunk sway could be masked by other changes related to their disease such as, for instance, a change in their lower extremity alignment (Mündermann et al., 2004).

## 2. Methods

In all, 19 subjects (7 females, 12 males; age:  $22.8 \pm 3.1$  yr; height:  $174.8 \pm 9.7$  cm; mass:  $70.5 \pm 16.3$  kg) participated in this study after giving written consent in accordance with the Institutional Review Board. Based on a priori sample size calculations, 19 subjects were sufficient to detect a 10% difference in the knee adduction moment. None of the subjects had previously been treated for any clinical lower back or lower extremity condition or had any activity-restricting medical or musculoskeletal condition. Healthy subjects rather than patients with knee osteoarthritis were assessed in this study to determine if the effects of increased medio-lateral trunk sway are decoupled from a mechanism of gait compensation used by patients with knee osteoarthritis. Subjects performed walking trials of normal gait and with increased medio-lateral trunk sway on a 10 m walkway in their personal walking shoes (Fig. 1). For the walking trials with increased medio-lateral trunk sway, subjects were instructed to move their trunk more from side to side and were given sufficient practice time so that they felt comfortable and were able to maintain a similar walking speed for the trials as with normal trunk sway. The degree of sway for the increased medio-lateral trunk sway trials and walking speed were self-selected by the subject.

The approach used to collect kinematic and kinetic data is identical to that described in previous investigations (Prodromos et al., 1985; Wang et al., 1990; Mündermann et al., 2004, 2005). Briefly, reflective markers were placed on the leg along the superior iliac spine, greater trochanter, lateral joint line of the knee, lateral malleolus, lateral aspect of the calcaneus and head of the fifth metatarsal. Marker data were captured using 7 high-speed cameras (120 frames/s; MCU240, Qualisys Medical AB, Gothenburg, Sweden). Ground reaction force data was collected using a force platform (sampling frequency: 120 Hz; Bertec Corporation, Columbus, OH) that was placed in the center of the walkway level with the ground. The positions of the joint centers at the hip, knee and ankle were located relative to the positions of the skin markers at the greater trochanter, the lateral joint line of the knee and the lateral malleolus, respectively. The position of the center of the knee and ankle joints in the frontal plane was located by identifying the mid-point of the line between the peripheral margins of the medial and lateral plateaus at the level of the joint surfaces and the mid-point between

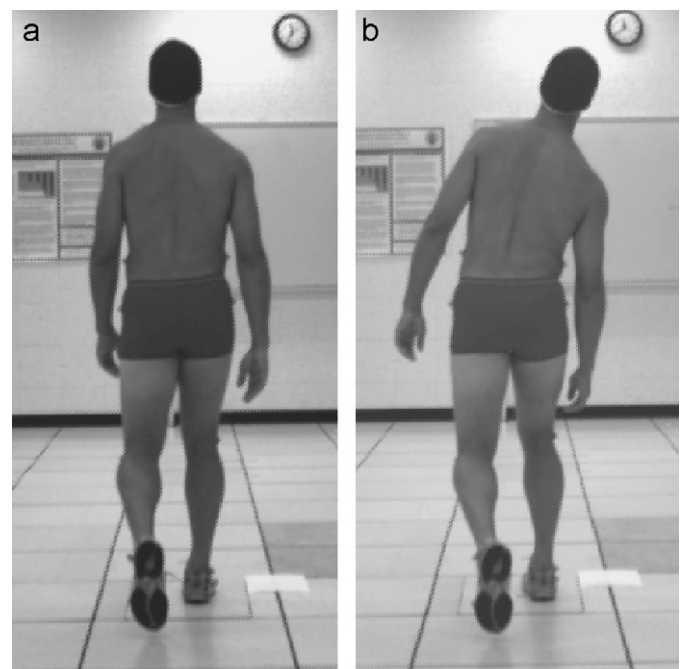


Fig. 1. These images show subject 1 when walking (a) with normal trunk sway and (b) with increased medio-lateral trunk sway. Note: This subject walked with a substantial increase in trunk sway that was equal or greater than that used by other subjects as determined by visual observation.

the medial and lateral malleoli, respectively. The hip joint center was located 2.5 cm distal to the mid-point of a line from the anterior superior iliac spine to the pubic tubercle. Each limb segment (thigh, shank and foot) was idealized as a rigid body, and intersegmental angles, external moments and forces were calculated from the position of the markers, ground reaction force measurements, and limb segment mass/inertia properties (Dempster and Gaughran, 1967) using a Newton–Euler inverse dynamics approach. The angular velocity and acceleration about the longitudinal axis of the segment were assumed to be negligible. It was assumed that the flexion–extension axis remained perpendicular to the plane of progression, the abduction–adduction and internal–external rotation axes of the hip, knee and ankle moved with the thigh, shank and foot segment, respectively (Prodromos et al., 1985). The axial forces at the ankle, knee, and hip were defined as the resultant intersegmental forces at these joints resolved along the long axis of the distal segment (foot, shank and thigh, respectively) taking into account the ground reaction force, the weight of the distal segment, and inertial forces (Prodromos et al., 1985). Medio-lateral trunk sway was defined as the frontal plane projection of the angle between a line connecting the midpoint of the trans-acromion line and the midpoint of the trans-anterior–superior-iliac-spine line, and the global vertical axis.

Discrete variables describing peak values of the ground reaction force and kinematics and kinetics for each joint in three dimensions were calculated using an in-house algorithm written in Mathematica version 4.1 (Wolfram Research Inc., Champaign, IL). Forces were normalized to bodyweight (%Bw), and moments were normalized to bodyweight and height (%Bw·Ht) to allow for comparison between subjects. Average values for three trials per condition were calculated for each joint before average values for each subject and condition were computed.

Separate repeated measures Student's *t*-tests with trunk sway condition as inter-subject factor were used to detect significant differences in discrete variables describing the three-dimensional intersegmental angles, moments and forces between the two trunk sway conditions. Bonferroni correction was applied to the significance level for the Student's *t*-tests to account for multiple comparisons ( $\alpha = 0.01$ ).

### 3. Results

When walking with increased medio-lateral trunk sway ( $10 \pm 5^\circ$ ), all subjects had reduced knee adduction moments with an average reduction of  $-65.0\%$  compared with walking with normal trunk motion (Fig. 2). On average, subjects landed with the knee in a more flexed position ( $+3.0^\circ$ ; Table 1). No differences were observed for the lateral ground reaction force and the axial loading rates at the ankle, knee and hip between the two trunk sway conditions (Table 1). All but one subject had increased knee and hip abduction moments when walking with increased medio-lateral trunk sway (average increase at the knee and hip:  $+60.1\%$  and  $+55.3\%$ , respectively). Similar to the knee, the first peak adduction moment at the hip was reduced for all subjects (average reduction  $-57.1\%$ ). These differences were observed despite the fact that subjects walked at similar speeds for both conditions (mean  $\pm 1$  SD speed: normal trunk sway  $1.48 \pm 0.17$  m/s; increased medio-lateral trunk sway  $1.44 \pm 0.15$  m/s;  $P = 0.406$ ). Post hoc power calculations revealed that differences with *P*-values smaller than 0.001 had a power greater than 95%.

### 4. Discussion

The results of this study showed that increased medio-lateral trunk sway in healthy subjects leads to a 65.0%

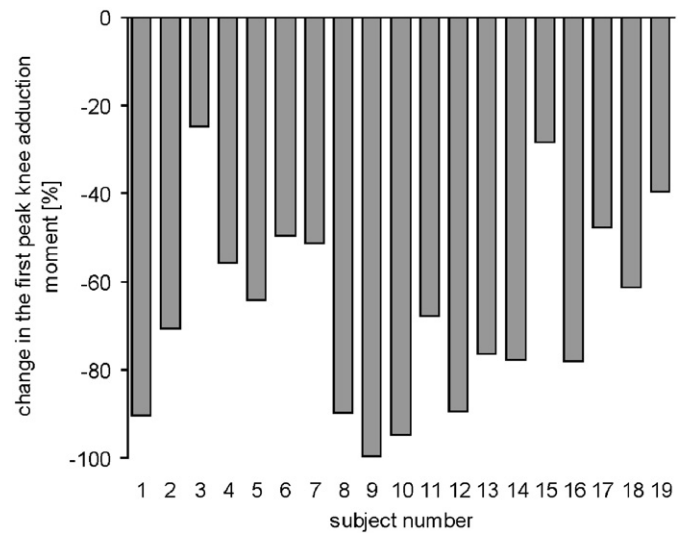


Fig. 2. Percentage changes in the first peak knee adduction moment for all 19 subjects when walking with increased medio-lateral trunk sway compared to walking with normal trunk sway.

reduction in the adduction moment at the knee during ambulation without significant differences in the lateral ground reaction forces and axial loading rates at the ankle, knee and hip. While there were similar changes to those reported for patients with knee osteoarthritis (Mündermann et al., 2005) in hip and knee abduction moments, the potential adverse secondary gait changes (decreased knee flexion angles at heel-strike, and greater axial loading rates at the ankle, knee and hip) were not present when subjects used increased lateral sway to reduce the adduction moment. Hence, increased medio-lateral trunk sway did affect lower extremity mechanics during ambulation, and some of these effects of increased medio-lateral trunk sway were decoupled from a mechanism of gait compensation used by patients with knee osteoarthritis. Moreover, increased medio-lateral trunk sway may be a simple yet effective non-invasive intervention in early knee osteoarthritis that amplifies patients' natural gait changes, leading to a reduction in medial compartment load without secondary changes in ambulatory mechanics, such as decreased knee flexion angle at heel-strike or increased ground reaction forces and axial loading rates at the major joints of the lower extremity. This may be especially important since it has been speculated that greater axial loading rates at the hip may contribute to the development of secondary hip osteoarthritis (Mündermann et al., 2005). In addition, walking with increased medio-lateral trunk sway may also be beneficial as preventative intervention for subjects who are at a higher risk of developing knee osteoarthritis.

In a previous study, Schröter et al. (Schröter et al., 1999) introduced the 'Entlastungsgang', a hip unloading gait. The 'Entlastungsgang' is a gait pattern with increased medio-lateral trunk lean of the straight back toward the affected limb during stance and greater hip abduction of the stance limb resulting in a wider foot placement.

Table 1  
Average (1 standard deviation) of the kinematic and kinetic variables tested during stance for the two trunk sway conditions ( $N = 19$ )

Variable	Trunk sway		Confidence interval of the difference	P-Value
	Normal	Increased		
Knee flexion angle at heel-strike (deg)	-0.9 (5.0)	2.1 (6.6)	<b>0.8; 5.1</b>	<b>0.009</b>
Maximum lateral ground reaction force (%Bw)	5.3 (2.2)	5.5 (3.0)	-6.0; 8.7	0.695
Maximum ankle axial loading rate (%Bw/s)	1280 (490)	1214 (356)	-303; 171	0.568
Maximum knee axial loading rate (%Bw/s)	1315 (490)	1269 (374)	-294; 203	0.702
Maximum hip axial loading rate (%Bw/s)	1286 (488)	1250 (371)	-284; 212	0.763
Maximum knee abduction moment (%Bw*Ht)	1.0 (0.5)	1.6 (0.7)	<b>0.4; 0.9</b>	<b>&lt;0.001</b>
Maximum hip abduction moment (%Bw*Ht)	2.0 (1.1)	3.1 (1.3)	<b>0.8; 1.5</b>	<b>&lt;0.001</b>
First peak knee adduction moment (%BwHt)	2.0 (0.7)	0.7 (0.6)	<b>-1.5; -1.0</b>	<b>&lt;0.001</b>
First peak hip adduction moment (%BwHt)	4.2 (1.4)	1.8 (1.5)	<b>-2.7; -2.0</b>	<b>&lt;0.001</b>

Confidence intervals and  $P$ -values of the difference are reported. Significant differences at the 1% significance levels are shown in bold.

Patients with hip pain were able to reduce the hip adduction moment during walking when instructed to employ the 'Entlastungsgang'. Patients received intensive gait training and physical therapy and were able to maintain the altered gait pattern for one year. Most patients reported substantial reductions in their pain level and perceived their altered gait as excellent or good. That study did not report on a control intervention, and the potential for a placebo effect in a population of patients with knee osteoarthritis should not be neglected. Nevertheless, the results of that study are promising in terms of a long-term change in hip load during walking and patient compliance after gait retraining. The potential of using walking with increased medio-lateral trunk sway as gait retraining, for patients with medial compartment knee osteoarthritis, has not been explored.

The results of this study do not explain the previously reported (Mündermann et al., 2005) differences in these variables between patients with medial compartment knee osteoarthritis and asymptotically matched control subjects. It is possible that other factors associated with knee osteoarthritis such as varus alignment (Hurwitz et al., 2002; Mündermann et al., 2004; van der Esch et al., 2005), a change in neuromuscular control (Hortobagyi et al., 2004, 2005; Hubley-Kozey et al., 2005), and/or reduced muscle strength (Fisher and Pendergast, 1997; Lewek et al., 2004) may contribute to these other gait changes. Subjects in this study were instructed to merely increase their medio-lateral trunk sway, and required minimal practice (less than three practice trials) to adopt the gait patterns presented here.

The subjects in this study were not instructed to increase hip abduction, yet the reductions in hip adduction moments were more than twice as large as those reported by (Schröter et al., 1999). Subjects in this study increased their medio-lateral trunk sway on average by  $10 \pm 5^\circ$ . However, the amplitude of trunk sway in patients with knee osteoarthritis is unknown. It is possible that our subjects walked with greater trunk sway for the increased medio-lateral trunk sway condition than what patients with knee osteoarthritis would adopt naturally, and than what patients with hip pain adopted after gait training and

physical therapy (Schröter et al., 1999). Nevertheless, it appears that gait retraining for walking with increased medio-lateral trunk sway has the potential of reducing the knee adduction moment to a much greater extent than other non-invasive or even surgical techniques (Prodromos et al., 1985; Kerrigan et al., 2002, 2003; Mündermann et al., 2004; Fisher et al., 2007).

Previous studies emphasized the role of hip abductor muscle strength for the success of gait retraining and gait adaptation in patients with hip pain (Schröter et al., 1999) and knee osteoarthritis (Mündermann et al., 2005), respectively. Stronger hip abductor muscles as reflected by greater external hip adduction moments during walking have been shown (Chang et al., 2005) to decrease the risk of osteoarthritis progression in the ipsilateral knee. Thus, the success of using gait retraining for walking, with increased medio-lateral trunk sway in patients with knee osteoarthritis, will likely depend on hip abductor muscle strength and may warrant the application of a muscle strengthening program in combination with a gait retraining program. Other physical limitations that could influence the efficacy of increased medio-lateral trunk sway in patients with knee osteoarthritis include diminished muscle force or balance, lower back conditions and increased energy expenditure. However, the relevance of these physical limitations will likely depend on the magnitude of increased medio-lateral trunk sway required to achieve clinically appropriate reductions in the knee adduction moment in patients with knee osteoarthritis.

Another factor that must be taken into consideration when prescribing gait retraining is the role of pain. Hurwitz et al. (Hurwitz et al., 2000) showed that pain has a protective effect for joint loading. In their study, patients took a nonsteroidal anti-inflammatory drug or placebo for two weeks after a 2-week washout of anti-inflammatory and analgesic treatment. Gait analysis before and after the drug treatment showed that the change in the peak external knee adduction moment between the two evaluations was inversely correlated with the change in pain. In addition, the pain level patients with hip pain was related to their ability to learn a load reducing gait where patients with

little pain had difficulties learning the load reducing gait (Schröter et al., 1999). Similarly, it is possible that patients with symptomatic knee osteoarthritis may naturally adopt a more pronounced unloading gait pattern than patients without any symptoms. The healthy subjects in our study had no pain, yet were able to quickly learn a gait pattern with increased medio-lateral trunk sway. However, it is unclear whether healthy subjects would be able to maintain such a gait pattern over a prolonged time.

In summary, walking with increased medio-lateral trunk sway produced changes in knee and hip moments in the frontal plane in healthy subjects similar to those reported for patients with medial compartment knee osteoarthritis. Substantial reductions in the knee adduction moment were observed when walking with increased medio-lateral trunk sway compared with normal trunk sway. These reductions were twice as high as reductions after high tibial osteotomy (Prodromos et al., 1985) and six times as high as reductions with bracing (Lindenfeld et al., 1997; Pollo et al., 2002) or footwear modifications (Kerrigan et al., 2002, 2003; Fisher et al., 2007). The altered gait pattern was associated with little changes in other variables describing the mechanical environment of the major joints of the lower extremity. This result supports the potential of using gait retraining for walking with increased medio-lateral trunk sway as treatment of patients with medial compartment knee osteoarthritis.

### Conflict of interest

None of the authors had any conflict of interest regarding this manuscript.

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