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Mechanical and Neuromuscular Changes with Lateral Trunk Lean Gait Modifications

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Abstract

Lateral trunk lean (LTL) is a proposed intervention for knee osteoarthritis but increased muscular demands have not been considered. The objective was to compare lower extremity and trunk muscle activation and joint mechanics between normal and increased LTL gait in healthy adults. Participants (n=20, mean age 22 years) were examined under two gait conditions: normal and increased LTL. A motion capture system and force plates sampled at 100 and 2000 Hz respectively were used to determine joint angles and external moments including LTL angle and external knee adduction moment (KAM). Surface electromyography, sampled at 2000 Hz, measured activation of six trunk/hip muscles bilaterally. Peak LTL angle, peak KAM, gait speed, and mean values from electromyography waveforms were compared between normal and LTL conditions using paired t-tests or 2-way analysis of variance. There was a significant ($p<0.05$) increase in peak LTL angle, decrease in first but not second peak KAM, and decrease in gait speed during LTL gait. There were significant ($p<0.01$) increases in external oblique and iliocostalis muscle activation during LTL gait. There was no change in activation for internal oblique, rectus abdominis, longissimus, and gluteus medius. LTL gait decreased early/mid-stance KAM demonstrating its ability to decrease medial compartment knee loading. Increases in external oblique and iliocostalis activation were present but small to moderate in size and unlikely to lead to short term injury. Longitudinal studies should evaluate the effectiveness of increased LTL for knee osteoarthritis and if the increase in muscular demands leads to negative long term side effects.

Key words: gait; lateral trunk lean; electromyography; knee adduction moment; motion capture

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1. Introduction

Approximately 16% of adults over 45 years of age have knee osteoarthritis (OA) [1]. Many interventions attempt to off-load the medial tibiofemoral compartment which is most commonly affected in knee OA [2,3]. For instance, increasing lateral trunk lean (LTL) during gait has been proposed as an intervention for patients with medial compartment knee OA [2,4-6]. For LTL gait, patients are instructed to increase trunk lean or sway in the frontal plane over the stance leg during gait. The rationale is that LTL shifts the center of mass laterally. This should move the ground reaction force laterally, thus reducing its lever arm to the knee center, and shifting knee loads from the medial to lateral compartment [4]. While direct measures of medial compartment loads are not readily available, the knee adduction moment (KAM) is used as a proxy [7].

Increasing LTL has resulted in decreased KAM in healthy participants and patients with knee OA [2,5,6]. LTL targets of 4, 8 and 12^{o} reduced peak KAM by 7, 21, and 25% respectively, compared with normal gait in healthy adults [2]. Another study found a 55% reduction in early stance peak KAM when healthy participants ambulated with increased LTL [6]. Furthermore, the timing of LTL impacted KAM and the trunk should cross the vertical axis towards the stance leg 32 ms prior to heel strike [6]. When patients with knee OA ambulated with LTL angle targets of 6, 9, and 12^{o}, they achieved early stance peak KAM reductions of 9, 12, and 15% respectively [5]. Therefore, increasing LTL during gait reduces the KAM, representing a shift in knee loads from the medial to lateral compartment.

There are potential barriers to using LTL gait as an intervention. Increased LTL in patients with knee OA resulted in greater energy expenditure, faster heart rate, and higher levels of perceived exertion compared to normal walking [8]. Some healthy individuals report pain or

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discomfort in the low back when ambulating with increased LTL [2]; although no such reports were found in patients with knee OA after one LTL walking session [5]. Potential adverse effects of increased LTL during gait should be investigated prior to recommending this as a knee OA intervention [5].

The biomechanical changes required for increasing LTL will increase demands on the neuromuscular system. However, the immediate demands on the trunk and hip musculature have only recently been studied [9]. Increasing muscle activation and force required for LTL gait could result in muscle soreness, fatigue, or injury since the muscles are not conditioned to these new, repetitive loads. Exploring the immediate muscular demands would provide insight into potential adverse effects associated with increasing LTL. The objective was to compare lower extremity and trunk muscle activation and joint mechanics (angles and moments) between normal and increased LTL gait in healthy adults.

2. Methods

2.1. Participants

Healthy adults (n=20) were recruited using convenience sampling from the community with advertisements for this cross-sectional study. Exclusion criteria included lower extremity or trunk pain within three months, lower extremity trauma or surgery within 12 months, or any health condition affecting gait. Group descriptors are provided in Table 1. The study was approved by the local research ethics board and informed consent was obtained from participants.

A sample size calculation estimated the number of participants [10]. LTL was previously shown to have a large effect (d=0.90) on KAM [5]. To be conservative, a lower effect size

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estimate (d=0.80) was used. Twenty participants were required assuming β=0.20, p=0.05, and one-tailed, paired t-test as the analysis for KAM.

The side to be assessed, termed ipsilateral side, was selected using simple randomization prior to data collection. Participants were required to draw labeled, masked papers. Right and left were allocated as the ipsilateral side for 13 and seven participants respectively.

2.2. Motion Capture

Data were collected with an eight camera motion capture system (OQUS 300+, Qualisys) sampled at 100 Hz and two synchronized force plates (BP400600, AMTI) sampled at 2000 Hz. Thirty reflective markers were placed on participants according to established guidelines [11,12]. Bilateral markers included: acromion, anterior and posterior superior iliac spines, femoral greater trochanters and lateral epicondyles, fibular heads, tibial tubercles, lateral malleoli, 1st and 5th metatarsal heads, and calcanei. Markers were also placed on the manubrium, xiphoid process, and spinous processes of six vertebrae (C7, T2, T7, L1, L3, L5). In addition, six markers were placed bilaterally on participants during static standing trials only to determine joint center position: femoral medial epicondyles, medial malleoli, and 2nd metatarsal heads.

2.3. Electromyography

Muscle activation was measured with a 16 channel surface electromyography (EMG) system sampled at 2000 Hz (Trigno, Delsys) (common mode rejection ration > 80 db at 60 Hz, bandwidth 20-450 Hz, signal amplification 1000 x). Electrodes were placed bilaterally over the following muscles using published guidelines (Table 2): external oblique, internal oblique, rectus abdominis, iliocostalis, longissimus, and gluteus medius [13,14]. Prior to placement, skin was debrided and shaved with a razor and cleaned with alcohol. Accurate electrode placement was confirmed with muscle palpation and submaximal contractions.

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2.4. Data Acquisition

Prior to data collection, participants were taught to ambulate with increased LTL using verbal instructions and demonstrations. They were instructed to increase medial-lateral trunk sway and lean over their stance leg. This was done for both sides such that they leaned to the right during right stance and leaned to the left during left stance. They were allowed practice time and feedback was provided.

Data collection began with participants standing on a force plate to determine joint centers and measure body mass. Two gait conditions were collected: normal and LTL. Participants ambulated barefoot at self-selected speeds along an 8 meter, raised walkway. The normal condition preceded the LTL condition. During the LTL condition, real-time visual feedback of the LTL angle was provided on a large monitor using Visual3D (C-motion). Feedback was only provided for the ipsilateral side. An 8° target was set based on previous research demonstrating substantial reduction in peak KAM (21%) with 8° of LTL [2]. Participants were permitted at least two warm-up trials for each condition, including practice to become accustomed to the LTL visual feedback. Five trials were collected for each condition.

2.5. Maximum Voluntary Isometric Contractions

Next, participants performed maximal voluntary isometric contractions (MVIC) that were used to amplitude normalize gait EMG waveforms. The following contractions (with targeted muscles) were performed [15]: 1) sit-up (rectus abdominis), 2) V-sit-up (rectus abdominis), 3) right and 4) left axial rotation in sitting (internal and external oblique), 5) back extension in prone (iliocostalis, longissimus), 6) right and 7) left axial rotation in prone combined with back extension (iliocostalis, longissimus), and 8) hip abduction in sidelying (gluteus medius). An investigator provided manual resistance for each contraction. The investigator placed his hands

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just medial to the anterior shoulders or over the scapula of the participant depending on the required force direction for exercises 1-7. For hip abduction, the investigator placed his hand slightly superior to the lateral knee. Participants were instructed to provide maximal force and the investigator met this force. Verbal encouragement was provided to ensure a maximal contraction. Participants performed at least one practice trial and two collection trials for each contraction. A 60 second rest was provided between trials.

2.6. Data Processing

Positional reflective marker and force plate data were filtered with 4th order Butterworth filters, with cut-off frequencies of 6 Hz and 20 Hz respectively. Knee and ankle joint centers were determined as the mid-point between medial and lateral epicondyle (knee) and malleolus (ankle) markers. Hip center was defined based on anatomic landmarks using a previously described method [16]. Local co-ordinate systems were established on limb segments using previously reported methods [17]. Consistent with previous research, LTL angle was calculated by projecting the thorax proximal-distal axis onto the frontal plane [4,18]. The mid-point between the xiphoid process and T7, and the mid-point between the manubrium and T2 represented the proximal and distal ends respectively of the thorax axis. The angle between this projected axis and the lab vertical axis represented the LTL angle. Net external moments were calculated through inverse dynamics, using previously published segment inertial properties, expressed in joint co-ordinate systems, and amplitude normalized to body mass [19,20].

EMG signals were full-wave rectified and low-pass filtered (Butterworth, 2nd order dual-pass) at 6 Hz to produce a linear envelope [21]. Maximum EMG amplitudes from MVIC exercises were determined using a 100 ms moving average window and were used to amplitude normalize gait EMG waveforms.

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Angle, moment, and EMG waveforms were time normalized to 100% gait cycle, with the gait cycle defined as the period between successive ipsilateral side heel strikes. The first heel strike was identified using the force plate while the subsequent heel strike (not on the force plate) was determined using a kinematic based technique [22]. The study variables included peak LTL angle, first peak KAM in early stance, and second peak KAM in late stance for the ipsilateral side only. To examine if LTL gait required greater muscle activation, an EMG amplitude variable was calculated. Specifically, the mean signal was calculated for EMG waveforms (EMG-mean) from both ipsilateral and contralateral sides. It was assumed that both sides would control trunk movement by acting either concentrically or eccentrically. Gait speed was determined by tracking forward progression of the posterior superior iliac spines markers.

The LTL condition had decreased gait speeds. In order to match speed between conditions, three of the five fastest trials were selected for the LTL condition for each participant. Similarly, three of the five slowest trials were selected for the normal condition. Study variables (e.g. EMG-mean) were determined for each trial and averaged over three trials for each participant over each condition.

2.7. Statistical Analysis

Descriptive statistics were determined for demographic and study variables. Paired, one tailed t-tests compared gait speed, peak LTL angle, and first and second peak KAM between normal and LTL conditions for the ipsilateral side. Repeated measures, 2-way analysis of variance (ANOVA) compared EMG-mean values between sides (ipsilateral vs. contralateral) and conditions (normal vs. LTL) for each muscle. Effect sizes (d) were calculated for the above comparisons to examine the size of difference between conditions [23]. Effect sizes were interpreted as small, moderate, and large according to values of 0.2, 0.5, and 0.8 respectively

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[10]. A threshold of $p<0.05$ was used for statistical significance. These statistical analyses were completed using SPSS version 20.0 (IBM). To determine at what time during gait there existed differences in EMG between conditions, the mean difference 95% bootstrap confidence intervals (CI) were calculated along the entire curve [24,25]. This was only performed for muscles that had significantly different EMG-mean values between conditions. Participant EMG data were resampled 1000 times. For each iteration, the difference between group means for LTL and normal conditions was determined. From these 1000 waveforms representing condition differences, the 95% CI was determined at each 1% of the gait cycle. If the 95% CI did not include 0 for a specific time point, then significant differences in normal and LTL conditions existed at that time. A custom program in Matlab 7.14 (Mathworks) was used for this analysis.

3. Results

Descriptive statistics and effect sizes for study variables are provided in Table 3. Despite matching trials based on speed, there was a significant decrease in gait speed ($t=2.35$, $p=0.03$, small to moderate effect) for the LTL condition. Peak LTL angle was significantly increased ($t=-14.64$, $p<0.01$, large effect), and first peak KAM was significantly decreased ($t=5.23$, $p<0.01$, moderate to large effect) for the LTL compared to the normal condition (Fig. 1, Table 3). There was no significant change ($t=1.47$, $p=0.16$) in the second peak KAM (Fig. 1, Table 3).

EMG data were missing for two participants because of difficulty establishing good skin contact with the electrodes, likely because these participants were overweight. An additional participant had missing rectus abdominis data, and another had missing iliocostalis data due to technical problems. For external oblique muscles, there was a significant condition effect ($F=11.89$, $p<0.01$), but non-significant side ($F=0.07$, $p=0.80$) or interaction ($F=2.40$, $p=0.14$) effects. External oblique EMG-mean values were higher for the LTL condition, producing small

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to moderate effect sizes bilaterally (Fig. 2, Table 3). Additionally, iliocostalis muscles showed a significant condition effect (F=12.80, p<0.01), but non-significant side (F=0.09, p=0.77) or interaction (F=1.59, p=0.23) effects. Iliocostalis EMG-mean values were higher for the LTL condition, producing small to moderate effect sizes bilaterally (Fig. 2, Table 3). There were no significant (p>0.05) side, condition, or interaction effects for internal oblique, rectus abdominis, longissimus, and gluteus medius (Supplemental).

The 95% CI of the difference between normal and LTL conditions for the ipsilateral external oblique did not include zero between 53 to 85% of the gait cycle (Figure 2). This demonstrated that EMG was significantly higher during the LTL condition at this time. Likewise, contralateral external oblique, ipsilateral iliocostalis, and contralateral iliocostalis EMG were higher during the LTL condition predominantly between 0 to 32%, 52 to 90%, and 0 to 30% of the gait cycle respectively (Figure 2).

4. Discussion

Exaggerated LTL during gait in healthy individuals resulted in decreased early stance peak KAM, indicating decreased medial compartment knee loading for early to mid-stance. LTL gait required small to moderate increases in external oblique and iliocostalis activation. The clinical relevance of these findings, with respect to potential benefits of decreased KAM and potential detrimental effects of increased trunk motion and muscle activation, requires further investigation.

The KAM decrease with LTL gait (26% in first peak KAM) was similar to previous reports [2]. However, this effect is confounded by a decrease in gait speed (0.05 m/s) during LTL condition. Since slower speed is associated with lower peak KAM, the first peak KAM decrease may be partly explained by decreased speed [26]. Similarly, a study of healthy individuals

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ambulating with 8º LTL found decreased first peak KAM by 21%, no change in second peak KAM, and decreased gait speed by 0.06 m/s compared to normal gait [2]. Other studies found larger decreases (55 and 65%) in first peak KAM with LTL gait and no change in gait speed [6,27]. A study in patients with knee OA reported significant decreases in first (11%) and second (18%) peak KAM along with no change in speed during 9º LTL gait [5]. These findings suggest that increasing LTL during gait will decrease early stance KAM, with or without change in late stance KAM, and that this change is not solely due to decreasing gait speeds. Therefore, increasing LTL shifts loads from the medial to lateral knee compartment which could benefit patients with medial compartment knee OA.

While decreased KAM is a positive finding, LTL gait placed a greater demand on external oblique and iliocostalis. Their activity during LTL gait was increased during the stance phase of the opposite leg around or just after heel strike (Fig. 2). In other words, left sided muscles increased activity around right heel strike as the trunk leaned to the right, and vice versa. These muscles were likely eccentrically contracting as the trunk leaned towards the opposite side. This increased muscle activity was present despite slower gaits speeds for LTL gait, which is counter to the decrease in trunk muscle activity that normally accompanies slower speeds [28]. Thus, the increase in EMG was due to LTL gait and not slower speeds. The effect sizes for the increase in external oblique and iliocostalis activation were small to moderate, with EMG-mean values increasing by only 0.95 to 2.06 %MVIC. Such increases are unlikely to result in immediate muscle injury. However, signs of muscle fatigue may be observed with levels of sustained activation as low as 2% of MVIC. The role of such fatigue in the development of pain or muscle injury is unclear, although it is assumed to be a potential contributing factor to low

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back pain [29]. Therefore, long term potential negative side effects of LTL gait require further research.

A recently published study also investigated EMG with LTL gait [9]. They found a similar increase in contralateral, but not ipsilateral, external oblique EMG with LTL gait. They measured EMG amplitude from heel strike to peak KAM which likely accounts for the nonsignificant change in ipsilateral external oblique EMG. In contrast, the current study examined EMG amplitude over the entire gait cycle. Also, the previous study demonstrated decreased ipsilateral gluteus medius and erector spinae EMG with LTL gait [9], while the current study found no change (gluteus medius, longissimus) or an increase (iliocostalis) in EMG amplitude. A greater decrease in gait speed during LTL gait (0.11 m/s) for the previous study and a difference in erector spinae electrode location partially explains the discrepancies. Also, similar decreases in ipsilateral gluteus medius EMG were found in early stance during LTL gait for the current study (Supplemental). However, gluteus medius EMG amplitude over the entire gait cycle was not different between normal and LTL conditions. Regardless, there is an increase in EMG for some trunk muscles with LTL gait.

This study has limitations. Healthy, young participants were recruited which limits generalizability. LTL gait is intended for patients with knee OA. Changes in their gait, joint mechanics, and neuromuscular function due to OA and age might impact if they can adequately control LTL and if it will result in similar KAM reductions. There is likely relative movement of skin mounted markers in relation to underlying bone which is a concern in obese participants. Obtaining quality EMG signals from obese participants is also more difficult and the current sample included three obese participants (body mass index>30 kg/m^2).

5. Conclusions

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Increasing LTL during gait toward the stance limb reduces early stance KAM which is a proxy for medial compartment knee loading. LTL gait produces small to moderate increases in iliocostalis and external oblique muscle activation on the side contralateral to the LTL, which could be associated with muscle fatigue and pain over the long term. Longitudinal studies are needed to determine if LTL can produce beneficial effects for patients with knee OA without predisposing them to low back pain as a result of the altered gait.

Conflicts of interest

There are no conflicts of interest to report.

References

[1] Jordan JM, Helmick CG, Renner JB, Luta G, Dragomir AD, Woodard J, et al. Prevalence of knee symptoms and radiographic and symptomatic knee osteoarthritis in African Americans and Caucasians: the Johnston County Osteoarthritis Project. J Rheumatol 2007;34(1):172-80.

[2] Hunt MA, Simic M, Hinman RS, Bennell KL, Wrigley TV. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by real-time biofeedback. J Biomech 2011;44(5):943-7.

[3] Braga L, Renner JB, Schwartz TA, Woodard J, Helmick CG, Hochberg MC, et al. Differences in radiographic features of knee osteoarthritis in African-Americans and Caucasians: the Johnston county osteoarthritis project. Osteoarthritis Cartilage 2009;17(12):1554-61.

[4] Hunt MA, Birmingham TB, Bryant D, Jones I, Giffin JR, Jenkyn TR, et al. Lateral trunk lean explains variation in dynamic knee joint load in patients with medial compartment knee osteoarthritis. Osteoarthritis Cartilage 2008;16(5):591-9.

Robbins SM, Teoli A, Preuss R (2016). Mechanical and neuromuscular changes with lateral trunk lean gait modifications. Gait & Posture, 49, 252-257. doi:10.1016/j.gaitpost.2016.07.017

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[5] Simic M, Hunt MA, Bennell KL, Hinman RS, Wrigley TV. Trunk lean gait modification and knee joint load in people with medial knee osteoarthritis: the effect of varying trunk lean angles. Arthritis Care Res (Hoboken) 2012;64(10):1545-53.

[6] Mündermann A, Mündermann L, Andriacchi TP. Amplitude and phasing of trunk motion is critical for the efficacy of gait training aimed at reducing ambulatory loads at the knee. J Biomech Eng 2012;134(1):011010.

[7] Zhao D, Banks SA, Mitchell KH, D'Lima DD, Colwell CW Jr, Fregly BJ. Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. J Orthop Res 2007;25(6):789-97.

[8] Takacs J, Kirkham AA, Perry F, Brown J, Marriott E, Monkman D, et al. Lateral trunk lean gait modification increases the energy cost of treadmill walking in those with knee osteoarthritis. Osteoarthritis Cartilage 2014;22(2):203-9.

[9] Nüesch C, Laffer D, Netzer C, Pagenstert G, Mündermann A. Effect of gait retraining for reducing ambulatory knee load on trunk biomechanics and trunk muscle activity. Gait Posture 2016;47:24-30.

[10] Portney LG, Watkins MP. Foundations of Clinical Research: applications to Practice. 3rd ed. Upper Saddle River, NJ: Prentice Hall Health; 2009.

[11] Leardini A, Sawacha Z, Paolini G, Ingrosso S, Nativo R, Benedetti MG. A new anatomically based protocol for gait analysis in children. Gait Posture 2007;26(4):560-71.

[12] Leardini A, Biagi F, Merlo A, Belvedere C, Benedetti MG. Multi-segment trunk kinematics during locomotion and elementary exercises. Clin Biomech (Bristol, Avon) 2011;26(6):562-71.

[13] Preuss R, Fung J. Musculature and biomechanics of the trunk in the maintenance of upright posture. J Electromyogr Kinesiol 2008;18(5):815-28.

Robbins SM, Teoli A, Preuss R (2016). Mechanical and neuromuscular changes with lateral trunk lean gait modifications. Gait & Posture, 49, 252-257. doi:10.1016/j.gaitpost.2016.07.017

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[14] Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles [Internet]. Netherlands: SENIAM project; [cited 2016 Feb 16]. Available from: http://seniam.org/.

[15] Butler HL, Hubley-Kozey CL, Kozey JW. Characterisation of trunk muscle activation amplitude patterns during a simulated checkstand operation with continuously changing flexor and lateral moment demands. Ergonomics 2010;53(5):685-95.

[16] Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. J Biomech 1990;23(6):617-21.

[17] Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. Gait Posture 2009;30(2):173-80.

[18] Linley HS, Sled EA, Culham EG, Deluzio KJ. A biomechanical analysis of trunk and pelvis motion during gait in subjects with knee osteoarthritis compared to control subjects. Clin Biomech (Bristol, Avon) 2010;25(10):1003-10.

[19] Winter DA. Biomechanics and motor control of human movement. Toronto: John Wiley and Sons, Inc.; 1990.

[20] Schache AG, Baker R. On the expression of joint moments during gait. Gait Posture 2007;25(3):440-52.

[21] Hubley-Kozey CL, Robbins SM, Rutherford DJ, Stanish WD. Reliability of surface electromyographic recordings during walking in individuals with knee osteoarthritis. J Electromyogr Kinesiol 2013;23(2):334-41.

[22] Stanhope SJ, Kepple TM, McGuire DA, Roman NL. Kinematic-based technique for event time determination during gait. Med Biol Eng Comput 1990;28(4):355-60.

Robbins SM, Teoli A, Preuss R (2016). Mechanical and neuromuscular changes with lateral trunk lean gait modifications. Gait & Posture, 49, 252-257. doi:10.1016/j.gaitpost.2016.07.017

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[23] Dunlap WP, Cortina JM, Vaslow JB, Burke MJ. Meta-analysis of experiments with matched groups or repeated measures designs. Psychol Methods 1996;1(2):170-7.

[24] Lenhoff MW, Santner TJ, Otis JC, Peterson MG, Williams BJ, Backus SI. Bootstrap prediction and confidence bands: a superior statistical method for analysis of gait data. Gait Posture 1999;9(1):10-7.

[25] Dixon PC, Stebbins J, Theologis T, Zavatsky AB. Ground reaction forces and lower-limb joint kinetics of turning gait in typically developing children. J Biomech 2014;47(15):3726-33.

[26] Robbins SM, Maly MR. The effect of gait speed on the knee adduction moment depends on waveform summary measures. Gait Posture 2009;30(4):543-6.

[27] Mündermann A, Asay JL, Mündermann L, Andriacchi TP. Implications of increased medio-lateral trunk sway for ambulatory mechanics. J Biomech 2008;41(1):165-70.

[28] Anders C, Wagner H, Puta C, Grassme R, Petrovitch A, Scholle HC. Trunk muscle activation patterns during walking at different speeds. J Electromyogr Kinesiol 2007;17(2):245-52.

[29] van Dieën JH, Westebring-van der Putten EP, Kingma I, de Looze MP. Low-level activity of the trunk extensor muscles causes electromyographic manifestations of fatigue in absence of decreased oxygenation. J Electromyogr Kinesiol 2009;19(3):398-406.

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Table 1
Group descriptors of the study sample (n=20, 14 men).

Variable	Mean (SD)	Minimum, Maximum
Age (y)	22 (4)	19, 35
Mass (kg)	76.08 (18.85)	47.90, 114.73
Height (m)	1.73 (0.09)	1.57, 1.88
Body Mass Index (kg/m^2)	25.16 (5.26)	17.38, 39.24

Note. SD, standard deviation.

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Table 2
Location of electrodes over the muscle sites.

Muscle*	Location	Orientation
External Oblique [13]	15 cm lateral to the umbilicus, anterior to axillary line	45° angle
Internal Oblique [13]	One finger width medial and superior to the anterior superior iliac spine	Horizontal
Rectus Abdominis [13]	Two finger widths lateral to the umbilicus	Vertical
Iliocostalis [14]	One finger width medial from the line between the posterior superior iliac spine to the lowest point of the twelfth rib, at the level of second lumbar vertebrae	In the direction of the line between the posterior superior iliac spine to the lowest point of the twelfth rib
Longissimus [14]	Two finger widths lateral from the spinous process of the first lumbar vertebrae	Vertical
Gluteus Medius [14]	50% of the distance between the iliac crest and the greater trochanter	Along the line between the iliac crest to the greater trochanter

Note. *References are provided.

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Table 3
Descriptive statistics for the study variables and effect sizes between conditions.

Variable	Sample Size	Side	Condition	Mean (95% CI)	Effect Size*
Speed (m/s)	20	-	Normal	1.19 (1.13, 1.25)	-0.38
			LTL	1.14 (1.09, 1.19)	
Peak LTL Angle (°)	20	Ipsi	Normal	2.54 (1.77, 3.31)	3.00
			LTL	9.24 (8.05, 10.43)	
First Peak KAM (Nm/kg)	20	Ipsi	Normal	0.43 (0.38, 0.48)	-0.76
			LTL	0.32 (0.25, 0.39)	
Second Peak KAM (Nm/kg)	20	Ipsi	Normal	0.30 (0.25, 0.35)	-0.17
			LTL	0.27 (0.21, 0.33)	
External Oblique EMG-Mean (%MVIC)	18	Ipsi	Normal	5.15 (3.12, 7.18)	0.21
			LTL	6.10 (3.95, 8.25)	
		Contra	Normal	4.67 (3.22, 6.12)	0.45
			LTL	6.26 (4.47, 8.05)	
Internal Oblique EMG-Mean (%MVIC)	18	Ispi	Normal	9.59 (7.33, 11.85)	0.15
			LTL	10.39 (7.87, 12.91)	
		Contra	Normal	11.25 (8.60, 13.90)	0.18
			LTL	12.30 (9.53, 15.07)	
Rectus Abdominis EMG-Mean (%MVIC)	17	Ispi	Normal	6.09 (4.30, 7.88)	-0.16
			LTL	5.53 (3.96, 7.10)	
		Contra	Normal	6.13(3.81, 8.45)	-0.03
			LTL	5.99 (3.43, 8.55)	
Iliocostalis EMG-Mean (%MVIC)	17	Ispi	Normal	4.78 (3.89, 5.67)	0.57
			LTL	6.04 (4.82, 7.26)	
		Contra	Normal	4.60 (3.37, 5.83)	0.62
			LTL	6.66 (4.73, 8.59)	
Longissimus EMG-Mean (%MVIC)	18	Ispi	Normal	5.18 (3.92, 6.44)	-0.03
			LTL	5.10 (3.77, 6.43)	
		Contra	Normal	5.03 (3.95, 6.11)	0.15
			LTL	5.44 (3.99, 6.89)	
Gluteus Medius EMG-Mean (%MVIC)	18	Ispi	Normal	9.97 (7.82, 12.12)	-0.05
			LTL	9.76 (7.82, 11.70)	
		Contra	Normal	9.29 (7.84, 10.74)	0.15

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	LTL	9.79 (8.12, 11.46)

Note. LTL, lateral trunk lean; KAM, knee adduction moment; CI, confidence interval; EMG-Mean, mean of the electromyography signal during one gait cycle; Ipsi, ipsilateral to selected side; Contra, contralateral to selected side.

*Positive values represent increases in the variables for the LTL condition while negative values represent decreases.

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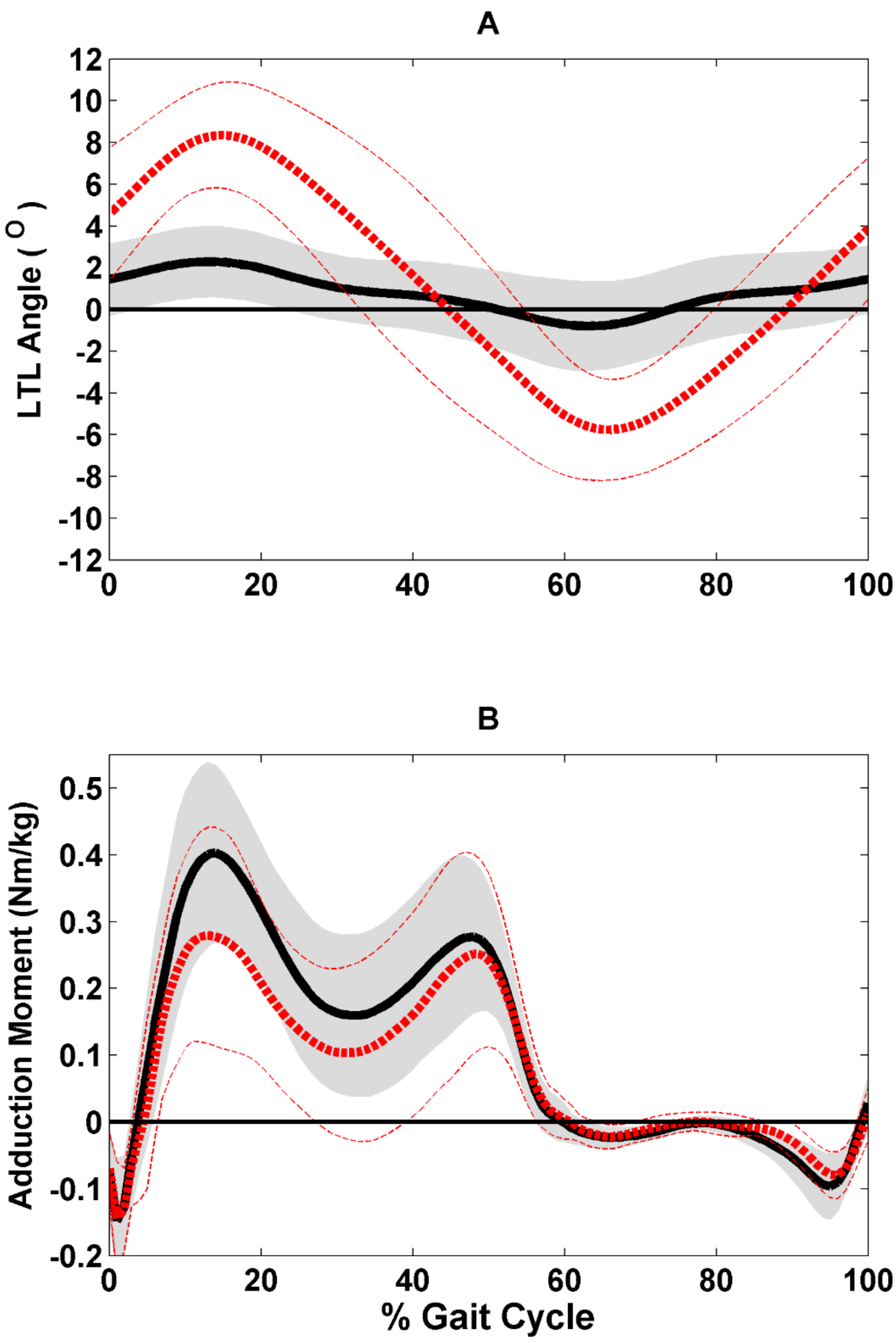

Fig. 1. The ensemble means for the entire sample for the lateral trunk lean (LTL) angle (A) and external knee adduction moment (B) for the normal (solid, black curves) and LTL (red, thick, dashed curves) conditions. The grey shaded area represents one standard deviation for the normal condition. The thin, red, dashed curves represent one standard deviation for the LTL condition.

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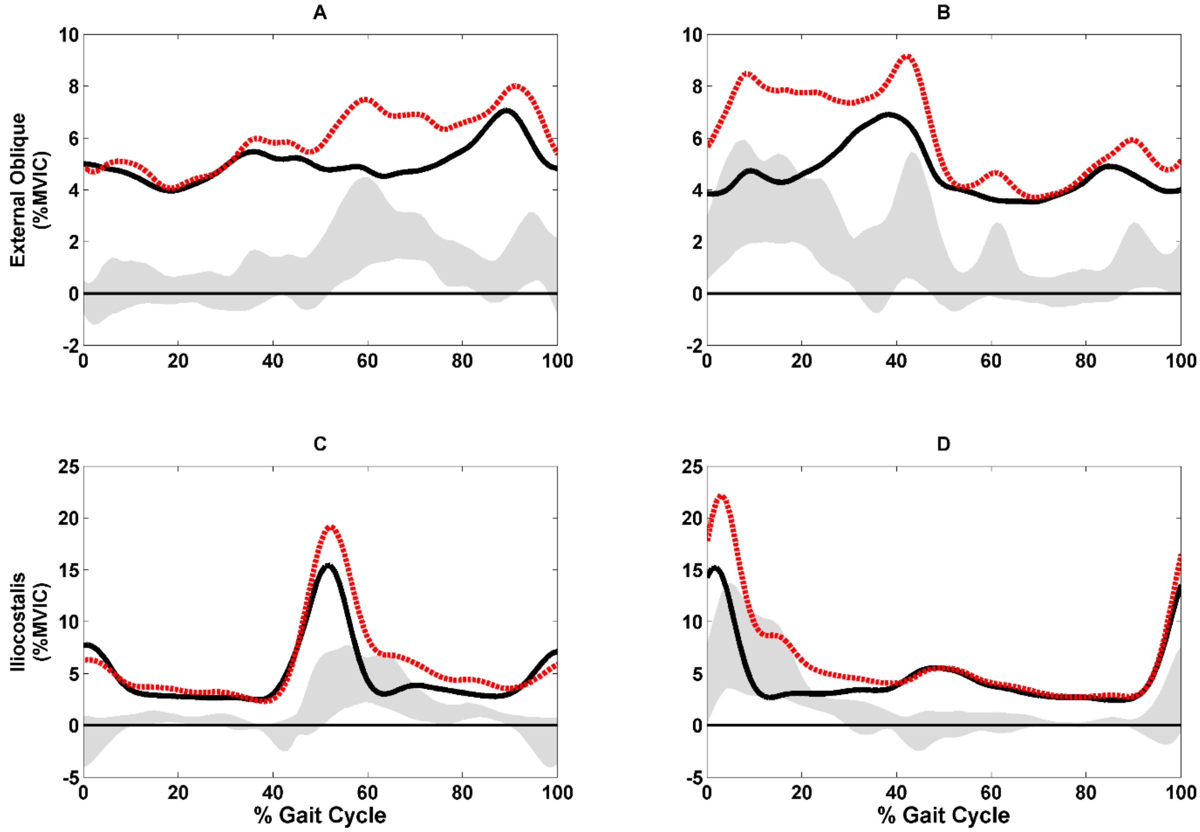

Fig. 2. The ensemble means for the entire sample for the external oblique electromyography for the ipsilateral (A) and contralateral (B) sides and iliocostalis electromyography for the ipsilateral (C) and contralateral (D) sides as a percentage of maximum voluntary isometric contraction (%MVIC). The normal (solid, black curves) and LTL (red, dashed curves) conditions are presented over the gait cycle where 0% represents the heel strike of the ipsilateral side and 100% represents the subsequent heel strike of the ipsilateral side. The grey shaded area represents the bootstrap determined 95% confidence interval of the difference between normal and LTL conditions.

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