THE COMPARATIVE GAIT EFFECTS OF SELECT WALKING SURFACES USING KINETIC AND EMG ANALYSES

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ABSTRACT

Purpose. This study investigated the EMG characteristics of muscles crossing the knee and the kinetics of the lower extremity during side-slope walking and other activities of daily living. We studied the difference in EMG data of the medial gastrocnemius and vastus lateralis muscles bilaterally and the relative rotation of the thigh to leg. **Methods.** Eleven outdoor workers (47.3 ± 13.9 years old) were recruited for this study. Participants walked on a 0° flat surface, 5° and 10° side-sloped surfaces, 10° inclined treadmill and ascended stairs. The EMG activity and rotation about a vertical axis during stance phase were analyzed. **Results.** Except for minor variations, ANOVA showed no significant difference in EMG activity between the walking surfaces, furthermore, the relative rotation of thigh-to-leg showed little or no differences between the variables. Multivariate ANOVA showed p-values between 0.1602 and 0.9943 when comparing the EMG data of all side-sloped surfaces. The relative rotation of the thigh to the leg showed p-values of 0.7837 and 0.9813 when comparing the left 0° to 10° and right 0° to 10°, respectively. **Conclusions.** The results of this study indirectly indicate that when considering rotation about a vertical axis and EMG activity, there is little difference in knee joint loading.

Key words: gait, kinetics, EMG, side-sloped walking surface

Introduction

This study was undertaken to determine the electrical activity of the lower extremity skeletal muscles associated with the tibio-femoral joint and the rotational differences between the leg and thigh during gait over different walking surfaces. There is a large amount of research on gait and knee joint effects over level surfaces [1], ascending or descending stairs [2, 3] and on ramps [4, 5]. Knee joint power as a product of joint moments and angular velocity was also shown to have significant increases with extreme (39%) upslope walking. Ground reaction forces and select gait parameters on cross-sloped walking surfaces have also been previously studied. While many activities of daily living (ADL) typically occur on flat surfaces, walking surfaces in physical training, rehabilitation and industrial settings could include slopes of various directions (side, incline and decline) and surfaces of different textures (smooth, gravel, concrete, rocky, etc.).

In the lower extremities, research has shown that the quadriceps and gastrocnemius muscles are major contributors to knee joint loading especially during stance phases [6]. In the quadriceps muscle group, the vastus lateralis is the largest component and is inserted on the lateral border of the patella, which then blends with the quadriceps tendon. The gastrocnemius muscle originates near both condyles of the femur and both com-

ponents of the muscle course distally to insert on the posterior aspect of the calcaneus bone of the foot [7]. Data have shown axial joint force peak magnitudes during stance phases at 810 N and 860 N for the vastii and gastrocnemius muscles, respectively [8]. The previous study also showed knee joint force during the swing phase to be negligible compared to stance values. It was also reported that the vastus lateralis (VL) and the medial gastrocnemius (GM) produce more force in individuals who experience patellofemoral pain [9].

Wireless inertial measurement units (IMUs) can be used to monitor movement and gait in test subjects. These IMU devices provide data that include acceleration, rotation and magnetic field parameters that go beyond the current wearable units that monitor only acceleration [10]. The quantification of motions of everyday living by using accelerometers can provide useful classification data and include sitting, standing, walking, stair climbing and cycling [11]. The combination of accelerometer and gyroscope data utilizing body-mounted sensors has been demonstrated by measuring knee movement during gait [12]. The accurate and real-time measurement of the posture parameters of human body segments with magnetometers, gyroscopes and accelerometers has been previously demonstrated [13].

Published research concerning the relationship between knee problems and tasks performed at work have shown mixed results. Male farm workers, forestry workers and postal workers have not demonstrated an increased risk of knee osteoarthritis [14]. Previous studies have shown a correlation between the physical

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demands of knee bending/squatting and the development of osteoarthritis [15]. It is possible that there are intervening factors unrelated to the knee that could impact the development of knee problems. A study by Murley et al. [16] looked at foot arch height differences and EMG activity during gait. The research showed only small differences in EMG readings in the GM and did not include the VL muscles. Investigation into the kinetics and muscle activity related to the knees in subjects who walk on a variety of surfaces could help illuminate the resultant effects as well as the potential for these surfaces to lead to knee dysfunction.

It was hypothesized for this study that there would be no or little significant difference between the EMG activity of the muscles under investigation when walking on flat, side-sloped, inclined surfaces or when ascending stairs. Furthermore, it was hypothesized that the electrical activity generated by the motor units close to the electrodes would be similar. Since the GM and VL muscles that were tested in each lower extremity of the subjects in this study cross the knee joint and have been shown to contribute significantly to knee joint forces, then walking on these test surfaces may not bring about significant contributions of the four muscles to increased knee joint loading. It was further anticipated that the IMU data may show differences in rotation of the leg relative to the thigh during the stance phase when walking on side-sloped surfaces.

Material and methods

Gait analysis on varying types of surfaces was performed on 11 healthy adults, eight males and three females (47.3 ± 13.9 years). Participants walked on a plywood platform of 12 meters (length) by 1.2 meters (width) at 0° (flat) and at 5° and 10° of side-slope (side-slope angle measured perpendicular to forward movement). The participants also ascended stairs and walked on a treadmill at a 10° incline. Institutional Review Board approval was obtained prior to the investigations and the informed consent of the participants was obtained. All work conformed to the Declaration of Helsinki principles.

The anthropometric data recorded included mean height (166.75 cm ± 8.6) and average weight (84.27 kg ± 19.6). The lower extremities were measured for leg length discrepancy (LLD) and it was determined that two participants had a shorter left lower extremity and two participants had a shorter right lower extremity. A LLD ≥ 0.6 cm was classified as significant [17]. Foot arch heights were measured utilizing the navicular bone as a reference and it was determined that only one participant was at the high normal range [18].

For testing, each subject wore a pair of standard leather work boots (Red Wing Shoes, USA, 6-inch, lace-up boot). Participants practiced walking on each surface before data collection. Wireless EMG devices (Shimmer

Research, Ireland) were attached via 15 mm Ag/AgCl surface electrodes spaced 25 mm apart using 200 mm leads. Before attachment, the selected area of skin was swabbed with 70% isopropyl alcohol and allowed to dry. The raw EMG data were collected (1000 Hz) and band-pass filtered (10–500 Hz) to remove motion artifacts. For each subject, the vastus lateralis (VL) and medial head of the gastrocnemius (GM) were palpated bilaterally. Electrodes were applied bilaterally to the VL muscle at a midpoint between the greater trochanter and the lateral epicondyle of the femur. For the GM, electrodes were applied bilaterally to the GM at a midpoint between the medial epicondyle of the femur and the medial malleolus. After practice, the isometric maximum voluntary contraction (MVC) of each muscle was recorded for the participant and used as the upper limit in for later calculations. The MVC of the vastus lateralis was tested while the participant was in a seated position and attempted to extend their lower leg against an immovable object. The MVC of the gastrocnemius was recorded simultaneously for both legs with the participant standing on their toes and contracting their muscles. EMG data were synchronized with 300 Hz video recordings to determine gait cycle phases.

Wireless IMU devices (MEMSense, USA) were attached to the subject's lower extremities bilaterally. An IMU device was placed on each thigh of the participant at a midpoint between the greater trochanter and the epicondyle of the femur. Each leg of the participant had an IMU device attached at the midpoint of the condyle and the malleolus of the tibia. The IMU devices have a bandwidth of 150 Hz and provide three axes each with acceleration, rotation, and magnetic field data. Magnetometer data were used to identify the time when the foot was in contact with the ground (Fig. 1) during all side slope and treadmill walking. The gyroscope's y-coordinate data were used to identify the stance phase during stair walking. The angular velocity rotation in the x-direction was analyzed by normalizing the times between the thigh and leg, calculating the means and then finding the thigh-to-leg ratio.

Before data recording, the participants practiced their gait on each of the test surfaces. On the flat and side-sloped surfaces, subjects were asked to walk at a normal, self-selected speed on the 1.2 m wide by 12 m long platform, turn around, and return to the starting position. This provided data when the right or left thigh/leg was on the high side (LH) and when the right or left thigh/leg was on the low side (LL). The side slope of the heavily braced walking platform was adjustable from 0° to 5° to 10°. For each angle, the participants performed this cycle three times in one continuous sequence. The angle of the platform was changed after each run and the angle order was randomized for each participant. For the 10° inclined treadmill surface, participants were then asked to walk at normal gait speed. The ascending stair surface was comprised
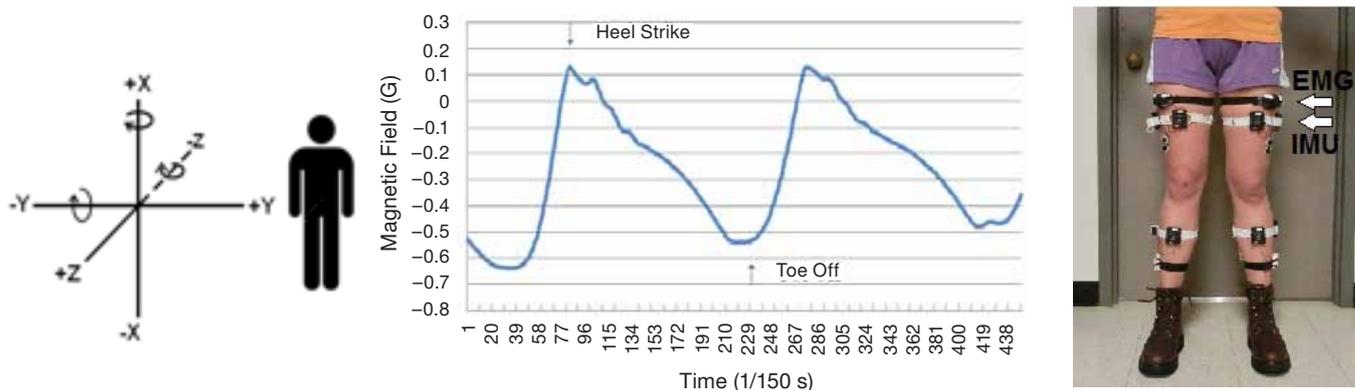
Figure 1. (left) Orientation of axes as the devices were worn by participants. (middle) Typical magnetometer data used to determine corresponding rotation data for analysis. (right) Participant wearing IMUs and EMGs

of 11 steps (rise = 19.05 cm and run = 29.21 cm) and participants were asked to engage at a cadence that was normal for them.

The collected 12-bit digital data were then converted to voltage, full-wave rectified and imported into the Delsys EMGworks (Delsys, USA) program for analysis. Each file was examined to determine the best representative stance phase peak for each test. The root mean square (RMS) was then calculated, exported to Excel (Microsoft, USA) and further analyzed to find the area under the curve using the trapezoid rule, with the results then summed. The data were normalized using the recorded MVC data for useful comparisons. Statistical analysis was performed with XLStat-Pro (Addinsoft, USA). Multivariate ANOVA, 2-way ANOVA with repeated measures, one-way ANOVA, and Pearson's product-moment correlation were used to make appropriate comparisons. The significance level was fixed at 0.05.

Results

Overall, multivariate ANOVA found there was no significant effect of angle on EMG data from the left lower extremity (Wilks' Lambda = 0.861, F (8,54) = 0.525, p = 0.832). The right lower extremity also showed there

was no significant effect of angle on EMG data (Wilks' Lambda = 0.0.836, F (8.54) = 0.633, p = 0.746 (Tab. 1).

The Pearson product-moment correlation of the EMG data shows close correlations between the 0°, 5°, 10° side-slope angles. There were nine of the r values that ranged between 0.401 and 0.520, out of 400. The average r value was 0.8187 ± 0.1083. Similar comparisons between the 10° side-slope, 10° inclined treadmill and ascending stairs data showed an average r value of 0.7748 ± 0.1346.

Although the left and right GM had slightly higher average treadmill values, the EMG data comparing 10° side-slope, 10° inclined treadmill (Tm) and ascending stairs data showed a mean of 37.01 ± 2.72 (Fig. 2). The increased GM Tm values might be expected in the 10° incline due to the forward alignment with the axis of progression and the increase in the force of plantar flexion.

When combining the RMS data from both the right and left lower extremities in each of the 11 participants in all three side-slope angles (Fig. 3), subjects #4 and #10 had noticeably lower values. Participant #10 was the oldest in the test group (age 65) and the associated aging and atrophy could account for the decreased

Table 1. Multivariate ANOVA of the Medial Gastrocnemius (GM), and Vastus Lateralis (VL) – Left Leg High (Left LH), Left Leg Low (Left LL), Right Leg High (Right LH), Right Leg Low (Right LL) at all angles and for all participants

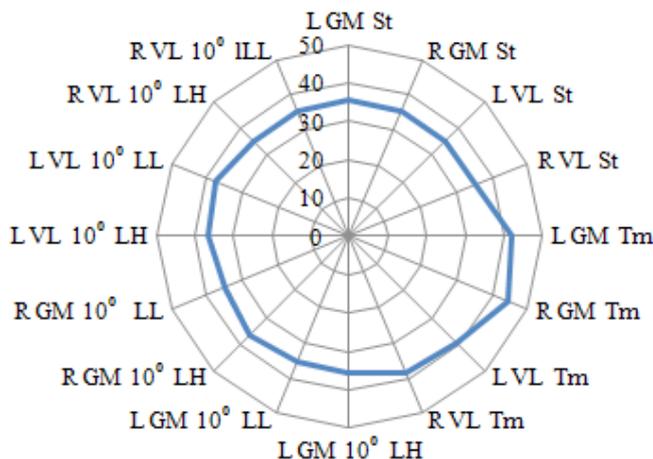| Source	MS	F	p-value
GM Left LH	0.1383	0.0057	0.9943
GM Right LL	31.6658	0.8048	0.4566
GM Right LH	80.0885	1.9481	0.1602
GM Right LL	20.3792	0.7224	0.4939
VL Left LH	17.2757	0.5363	0.5904
VL Left LL	8.0098	0.1976	0.8217
VL Right LH	12.6425	0.2007	0.8192
VL Right LL	16.2632	0.4883	0.6185

Figure 2. Averaged % MVC data for all 11 subjects at 10° side-slope, 10° incline on treadmill (Tm) and ascending stairs (St). The vertical axis represents 0% – 50% MVC
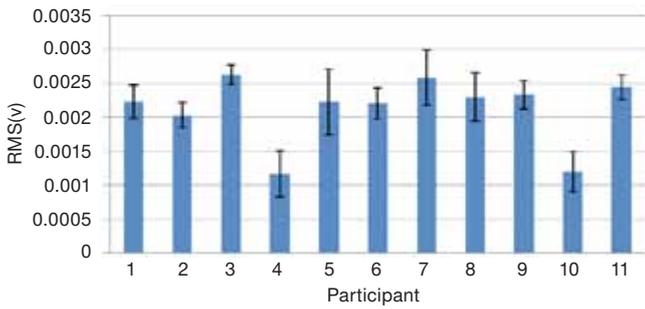
Figure 3. Averaged RMS data including the right
and left lower extremities at 0°, 5°, 10°

Table 2. Rotation in the *x*-axis
(standing vertical axis of the subject): ANOVA values

Source	Mean	var(X)	1-α (95%)	F	p-value
Left LL 0°	1.1540	0.1353	0.2471	0.0764	0.7837
Left LH 0°	1.2397	0.1457	0.2564		
Left LL 10°	1.2650	0.1836	0.2878		
Left LH 10°	1.1943	0.1656	0.2734		
Right LL 0°	0.9695	0.0967	0.2090	0.0006	0.9813
Right LH 0°	1.0502	0.6261	0.5316		
Right LL 10°	0.9936	0.1465	0.2571		
Right LH 10°	1.0331	0.1025	0.2150		

electrical activity. Participant #4 was a diabetic with known neuropathies.

The LH/LL RMS values for the 5° and 10° side-slope surfaces indicates no significant difference between the LH and LL conditions at the 5° and 10° side-sloped angles. ANOVA shows $p = 0.9869$, $p = 0.5131$, $p = 0.7230$ and $p = 0.9336$ for the left GM 10°, left GM 5°, right GM 10° and right GM 5°, respectively. The VL data shows $p = 0.9603$, $p = 0.7004$, $p = 0.9755$, $p = 0.9030$ for the left VL 10°, left VL 5°, right VL 10° and right VL 5°, respectively. The Pearson Product Moment Correlation (r) values for the left GM 10° ($r = 0.93$), left GM 5° ($r = 0.88$), right GM 10° ($r = 0.88$), right GM 5° ($r = 0.42$), left VL 10° ($r = 0.85$), left VL 5° ($r = 0.76$), right VL 10° ($r = 0.63$) and right VL 5° ($r = 0.86$) show generally close correlations. The right GM 5° ($r = 0.42$) was the weakest.

The four participants fitting the criteria of LLD using ANOVA showed $F(19,79) = 0.2311$, $p = 0.9996$ when compared among themselves at 0°, and at 5° and 10° side-slope angles for GM and VL (LL/LH) data.

A two-factor with replication ANOVA was conducted on the IMU data to compare the effects of angle on the left (LL/LH) and right (LL/LH) lower extremities for angles 0° and 10°. The ratio of the leg-to-thigh rotation was considered (Tab. 2). The high *p*-values indicate that we cannot rule out the null hypothesis and indicates that there is little or no rotational difference between the left LH/LL 0° and 10° angles and the right LH/LL 0° and 10° angles.

An example of an *x*-axis gyroscope recording is given in Figure 4. It shows the characteristic higher rotation values seen in the thigh. This is expected given the rotation and flexion of the thigh that occurs by several muscle groups during gait. This participant had normal foot arch heights and no LLD.

It was noted that the participants with left short/right long LLD showed an increased std(X) of 0.4645 (LL) and 0.0376 (LH) when comparing the 0° to 10° surfaces. However there were only four participants in this LLD category. The treadmill at a 10° incline, the stairs data, and 0° flat and 10° side-sloped surfaces were compared to examine rotation in *x*. Two-factor with replication ANOVA showed left $F (3,79) = 0.1629$, $p = 0.9214$ and right $F (3,79) = 0.3992$, $p = 0.7540$ at a significance level of 0.05.
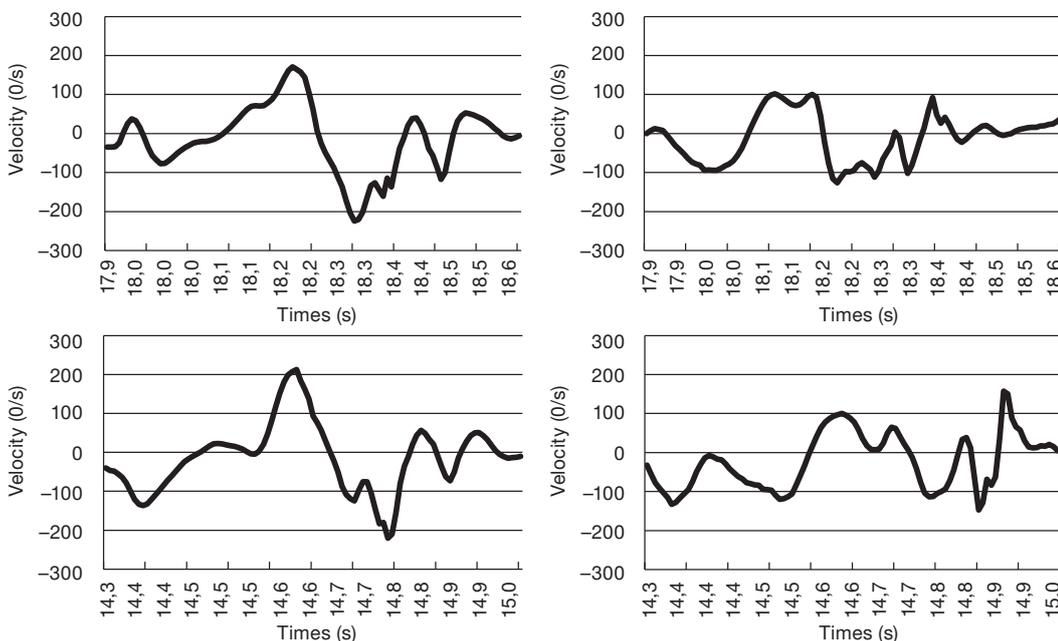

Figure 4. (top left) *x*-axis thigh rotation, velocity average of absolute values = 65.3, (top right) equivalent *x*-axis leg rotation, velocity average of absolute values = 50.4. Both graphs of the 0^0 flat surface and include LL data. (bottom left) *x*-axis thigh rotation, velocity average of absolute values = 66.1, (bottom right) equivalent *x*-axis leg rotation, velocity average of absolute values = 62.9, both graphs of the 10^0 side-slope surface and include LL data

Discussion

This study presented EMG and IMU data for the GM and VL bilaterally on several different walking surfaces. These muscles have been shown in literature to be the top contributors to knee forces during gait. We could not rule out our null hypothesis that there would be little or no difference in EMG activity in the tested muscles when walking on the various surfaces. The correlation between all surfaces was similar.

The Pearson values showed a strong degree of linear correlation between the normalized EMG variables. So while there appears to be little significant difference between the three side-slope surfaces, the *r* values indicate similarities.

Previous studies have shown little or no increase in EMG activity of the GM and VL muscles when flat surface walking, ramp walking and ascending stairs [19]. Our data support this assessment. We have demonstrated that there are little or no differences in EMG activity between flat surface and side-slope walking with the GM and VL muscles. Knee net forces have been shown to be similar during flat-surface walking and stair ascent [20]. Furthermore, the profiles for those activities were similar in all three force directions. There was a slight increase in EMG activity of the GM on the 10° inclined treadmill surface.

While it was expected that the IMU data would show increased rotation between the leg and the thigh in stance phase, this was not the case. These data showed a similar lack of significance between the 0° flat, 10° side-slope, 10° inclined treadmill and stair surfaces. The right lower extremity stair data did show higher var(X) values. Normal rotation at the knee during walking has been cited as ~20° between 20° and 40° of flexion [21]. We have shown this to be true when considering the relative rotations of the thigh to the leg on flat surfaces as well as the other surfaces in this study. Although the IMU std(X) values were comparatively higher, LLD and foot arch parameters did not appear to have a statistically significant effect on the data. There were two subjects in this study that had LLD with shorter left extremity and two subjects that had LLD with a shorter right extremity. The foot arches were within normal limits, where only one subject in this study had high normal arch height.

The right LL/LH rotation in *x* showed lower average values than the left side which may be due to laterality and the high percentage of right dominant individuals [22]. This study showed that symmetry in gait is not a valid assumption. This is further supported when looking at subjects expressing dorsi-flexor and plantar-flexor weaknesses [23].

Some the limitations of this study in relation to IMU data acquisition are similar to those found in marker-based video-motion analysis, which includes the motion of the bone relative to skin artifacts [24]. In addition, EMG signals are obtained and recorded from a wide area muscle and are also susceptible to motion artifacts [25]. Another limitation is that the types of surfaces and forms of ADL were limited to five in this study. Future research could include an examination of additional ADLs and walking surfaces. The $N = 11$ study size could be increased and additional anthropometric measurements could include limb, waist, and chest circumferences along with an estimation of % body fat.

Conclusion

This research showed no significant differences in GM/VL EMG data on a flat surface, 5° and 10° side-slope surfaces, a 10° inclined treadmill surface and when ascending stairs. The thigh-to-leg relative rotation ratios also showed no significant differences when subjects were in stance phase. The data presented would indirectly indicate similar knee joint loading within the confines of our experimental parameters. This study has provided useful data on the effects of side-slope walking surfaces in four significant knee related muscles and the vertical axis rotation of the thigh relative to the leg during stance phase. The information in this study could provide useful information to clinicians who evaluate the potential contributors or causes of knee-related injuries.

References

1. Perry J., Gait Analysis: Normal and Pathological Function. Slack Incorporated. Professional Book Division. Thorofare, NJ, USA, 1992.
2. Samuel D., Rowe P., Hood V. Nicol A., The biomechanical functional demand placed on knee and hip muscles of older adults during stair ascent and descent. *Gait Posture*, 2011, 34 (2), 239–244, doi: 10.1016/j.gaitpost.2011.05.005.
3. Brechter J.H., Powers C.M., Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait Posture*, 2002, 16 (2), 115–123, doi: 10.1016/S0966-6362(02)00090-5.
4. Lay A.N., Hass C.J., Nichols R., Gregor R.J., The effects of sloped surfaces on locomotion: an electromyographic analysis. *J Biomech*, 2007, 40 (6), 1276–1285, doi: 10.1016/j.jbiomech.2006.05.023.
5. McIntosh A.S., Beatty K.T., Dwan L.N., Vickers D.R., Gait dynamics on an inclined walkway. *J Biomech*, 2006, 39 (13), 2491–2502, doi: 10.1016/j.jbiomech.2005.07.025.
6. Kim H.J., Fernandez J.W., Akbarshahi M., Walter J.P., Fregly B.J., Pandy M.G., Evaluation of predicted knee-joint muscle forces during gait using an instrumented knee implant. *J Orthop Res*, 2009, 27 (10), 1326–1331, doi: 10.1002/jor.20876.
7. Gray H., Goss C., Gray's Anatomy. 29th ed. Lea & Febiger, Philadelphia 1975.

8. Sasaki K., Neptune R., Individual muscle contributions to the axial knee joint contact force during normal walking. *J Biomech*, 2010, 43 (14), 2780–2784, doi: 10. 1016/j. jbiomech.2010.06.011.

9. Besier T., Fredericson M., Gold G., Beaupré G., Delp S., Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls. *J Biomech*, 2009, 42 (7), 898–905, doi: 10.1016/j.jbiomech. 2009.01.032.

10. Zheng H., Black N.D., Harris N.D., Position-sensing technologies for movement analysis in stroke rehabilitation. *Med Biol Eng Comput*, 2005, 43 (4), 413–420, doi: 10.1007/BF02344720.

11. Bussmann H.B.J., Reuvekamp P.J., Veltink P.H., Martens W.L.J., Stam H.J., Validity and reliability of measurements obtained with an "activity monitor" in people with and without a transtibial amputation. *Phys Ther*, 1998, 78 (9), 989–998.

12. Heyn A., Mayagoitia R.E., Nene A.V., Veltink P.H., The kinematics of the swing phase obtained from accelerometer and gyroscope measurements. In: Proceedings of the 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Bridging Disciplines for Biomedicine. 31 Oct–3 Nov 1996, Amsterdam, Netherlands. *IEEE*, 1996, 2, 463–464.

13. Bachmann E.R., McGhee R.B., Yun X., Zyda M.J., Inertial and magnetic posture tracking for inserting humans into networked virtual environments. In: Proceedings of the ACM symposium on virtual reality software and technology, November 2001, Baniff, Alberta, Canada, 9–16.

14. Holmberg S., Thelin A., Thelin N., Is there an increased risk of knee osteoarthritis among farmers? A population-based case-control study. *Int Arch Occup Environ Health*, 2004, 77 (5), 345–350, doi: 10.1007/s00420-004-0518-1.

15. Vingård E., Osteoarthrosis of the knee and physical load from occupation. *Annal Rheumatic Diseases*, 1996, 55 (9), 677–684. doi:10.1136/ard.55.9.677.

16. Murley G., Menz H., Landorf K., Foot posture influences then electromyographic activity of selected lower limb muscles during gait. *J Foot Ankle Res*, 2009, 2 (35), doi: 10.1186/1757-1146-2-35.

17. Nichols P., Bailey N., The accuracy of measuring leg-length differences. *Br Med J*, 1955, 2 (4950), 1247–1248, doi: 10.1136/bmj.2.4950.1247.

18. Williams D.S., McClay I.S., Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Phys Ther*, 2000, 80 (9), 864–871.

19. Ciccotti M., Kerlan R., Perry J., Pink M., An electromyographic analysis of the knee during functional activities. I. The normal profile. *Am J Sports Med*, 1994, 22 (5), 645–650, doi: 10.1177/036354659402200512.

20. Costigan P., Deluzio K., Wyss U., Knee and hip kinetics during normal stair climbing. *Gait Posture*, 2002, 16 (1), 31–37, doi: 10.1016/S0966-6362(01)00201-6.

21. Wheeless C., Wheeless' Textbook of Orthopaedics. Available from: URL: http://www.wheelessonline.com/ [accessed September 01, 2011].

22. Õunpuu S., Winter D.A., Bilateral electromyographical analysis of the lower limbs during walking in normal adults. *Electroenceph Clin Neurophysiol*, 1989, 72 (5), 429–438, doi: 10.1016/0013-4694(89)90048-5.

23. Jeleń P., Wit A., Dudziński K., Nolan L., Expressing gait-line symmetry in able-bodied gait. *Dyn Med*, 2008, 7, 17, doi: 10.1186/1476-5918-7-17.

24. Benoit D.L., Ramsey D.K., Lamontagne M., Xu L., Wretenberg P., Renström P., Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait Posture*, 2006, 24 (2), 152–164, doi: 10.1016/j.gaitpost.2005.04.012.

25. Pullman S.L., Goodin D.S., Marquinez A.I., Tabbal S., Rubin M., Clinical utility of surface EMG: Report of the Therapeutics and Technology Assessment Subcommittee of the American Academy of Neurology. *Neurology*, 2000, 55 (2), 171–177, doi: 10.1212/WNL.55.2.171.

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