ANALYSIS OF MUSCLE FORCES DURING DOWNHILL WALKING

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The aim of this study was to analyse gait parameters and to quantify lower extremity muscles forces in downhill walking at different inclinations. Ten healthy male subjects walked at self-paced and at constant pre-set speed of 4 km/h on a ramp at different inclinations of -18°, -12°, -6° and 0°. Muscle forces were analysed by a musculoskeletal model (AnyBody) and were divided in four groups: quadriceps, hamstrings, calf muscles and shin muscles. Results showed significant increases in quadriceps and decreases in calf muscle forces with increasing inclination. Furthermore, quadriceps muscle forces were affected by walking speed. Hamstrings, quadriceps and calf muscle forces can be correlated with hip, knee and ankle joint moments, respectively. Therefore, it can be concluded that forces of major muscle groups can explain the joint extension moments.

KEY WORDS: AnyBody, inverse dynamics, musculoskeletal modelling.

INTRODUCTION: Hiking and mountaineering are popular sports in mountain regions (Bässler, 1997) and positive effects have been shown in several studies (Lee, Seo, & Chung, 2013). However, hiking and mountaineering can also cause pain and injuries of the musculoskeletal system (Blake & Ferguson, 1993). Most frequently pain was reported during downhill walking in the knee joint (Schwameder, 2004). Those findings are in agreement with results showing that the anterior cruciate ligament is highly loaded during downhill walking (Kuster, Wood, Sakurai, & Blatter, 1994). Following, several research groups analysed the effects of downhill walking (Schwameder, 2004) regarding postural adaptations (Leroux, Fung, & Barbeau, 2002; McIntosh, Beatty, Dwan, & Vickers, 2006), muscle activity (Franz & Kram, 2012), joint loading (Schwameder, Lindenhofer, & Müller, 2005), kinematics and joint kinetics (Lay, Hass, & Gregor, 2006). Graded walking is associated with an increase of lower extremity joint loading compared to level walking (Grampp, Willson, & Kernozek, 2000). It has been shown that joint moments at the knee, and to a lesser extent the ankle and hip, were affected by the inclination. Knee extension moments showed large increases with increased inclination (Redfern & DiPasquale, 1997). Since muscle forces are responsible for the resulting joint loadings, it would be interesting to know how the muscle forces change in respect to different inclinations. Furthermore, estimation of individual muscle forces can provide insight to tissue loading and can contribute to improved diagnosis and management of orthopaedic conditions (Erdemir, McLean, Herzog, & van den Bogert, 2007). Since direct measurement of muscle forces is generally not feasible in a clinical setting, non-invasive methods based on musculoskeletal modelling should be considered (Erdemir et al., 2007).
Reilly and Martens (1972) looked at quadriceps muscle force during level walking and stair descending for calculating knee joint loading. However, the muscle forces of the major lower extremity muscle groups during downhill walking at different inclinations and their correlation to joint moments have not been investigated so far. Therefore, the purpose of this study was to analyse the gait parameters speed, stride length and stride width and to quantify lower extremity muscle forces during downhill walking at different inclinations.

METHODS: Ten healthy male subjects (27.5 ± 4.2 yrs, 180.0 ± 3.8 cm, 76.2 ± 7.4 kg) were recruited for this study. The study was approved by the ethics board and informed consent was signed by all participants. Reflective markers according to the Cleveland Clinic Marker set (Motion Analysis Corp, Santa Rosa, USA) were attached. Following, subjects were asked to walk on a ramp (6 m x 1.2 m) with two integrated force plates (AMTI, Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA) at different inclination angles of -18°, -12°, -6° and 0°. Kinematic data was captured with a twelve-camera, marker based motion capture system (Vicon, Oxford, UK). Sampling frequency was 250 Hz and 2000 Hz for kinematic and kinetic data, respectively. Subjects had to perform three valid trials in each

condition for self-paced speed and for a constant pre-set speed of 4 km/h (≙1.11 m/s). Speed was controlled via a timing device (Brower, Brower Timing Systems, USA). One trial out of the three measured ones was used for further analysis. In the self-paced condition the trial with the speed closest to the mean speed of all three trials was used. In the constant condition the trial with the speed closest to the pre-set speed of 4 km/h was used. Kinematic data was further processed with Vicon Nexus (Vicon, Oxford Metrics Ltd, UK). Following, processed kinematic and kinetic data were imported a) into Visual3D (c-Motion Inc., Germantown, USA) to calculate the gait parameters stride length and stride width and b) into an inverse dynamic musculoskeletal modelling software (AnyBody 5.3, AnyBody Technology A/S, Aalborg, Denmark). A standard gait model available in the software was used for further calculating muscle forces (AMMR 1.5.1, GaitLowerExtremity). Muscle forces were summed up in the following groups: hamstrings (m. semitendinosus, m. semimembranosus, m. biceps femoris), quadriceps (m. rectus femoris, m. vastus lateralis, m. vastus medialis, m. vastus intermedius), calf muscles (m. gastrocnemius medialis, m. gastrocnemius lateralis, m. tibialis posterior lateralis, m. tibialis posterior medialis) and shin muscles (m. tibialis anterior, m. extensor digitorum longus, m. extensor hallucis longus). Each trial was time normalized to stance phase duration and the mean was calculated over all subjects.
Statistical analysis was calculated using SPSS 20.0 software. Tests for normality were undertaken and found to meet the requirements of parametric statistics. Therefore, differences between self-paced and constant condition over all inclinations were compared using mixed ANOVA. Differences in average muscle force across stance phase in relation to different inclinations separately for each condition were calculated using one-way ANOVA. In case of significance, a Bonferroni post-hoc test was performed for pairwise comparison.

RESULTS: Table 1 shows the gait parameters speed, stride length and stride width for both conditions at all inclinations. A significant difference ($p = 0.022$) was found for speed between the self-paced and constant condition. In the self-paced condition subjects walked faster compared to the constant condition, being significant ($p = 0.016$) during level walking. For stride length and stride width no significant differences between conditions were found.

Table 1: Gait parameters (mean ± SD) for both conditions and all inclinations.

Condition	inclination	speed [m/s]*	stride length [m]	stride width [m]
self-paced	*0°*	1.20 ± 0.09 ⁺	1.42 ± 0.11	0.14 ± 0.02
	-6° ⁽²⁾	1.14 ± 0.10	1.38 ± 0.10	0.17 ± 0.03
	-12° ⁽³⁾	1.18 ± 0.14	1.35 ± 0.09	0.17 ± 0.03
	-18° ⁽⁴⁾	1.12 ± 0.17	1.28 ± 0.15	0.18 ± 0.02
Constant	*0°*	1.11 ± 0.01	1.38 ± 0.08	0.15 ± 0.01
	-6° ⁽²⁾	1.11 ± 0.01	1.38 ± 0.08	0.16 ± 0.03
	-12° ⁽³⁾	1.11 ± 0.01	1.35 ± 0.09	0.17 ± 0.03
	-18° ⁽⁴⁾	1.11 ± 0.01	1.28 ± 0.09	0.18 ± 0.03

Significant ($p < 0.05$) differences between conditions over all inclinations* and pairwise comparison⁺.

Figure 1 shows quadriceps, hamstrings, calf muscle and shin muscle forces during stance phase in the constant condition. Quadriceps and calf muscle forces were the highest and while quadriceps muscle forces increase with increasing inclination, calf muscle forces decrease. This is also shown in Table 2 presenting the average muscle forces across stance phase. With increasing inclination quadriceps muscle forces increase and calf muscle forces decrease significantly ($p < 0.05$) compared to level walking. No significant difference between conditions was found for any average muscle force. However, significant ($p < 0.05$) differences in average muscle force across stance phase were found in both conditions in respect to different inclinations for all muscle groups except the shin muscles (Table 2).

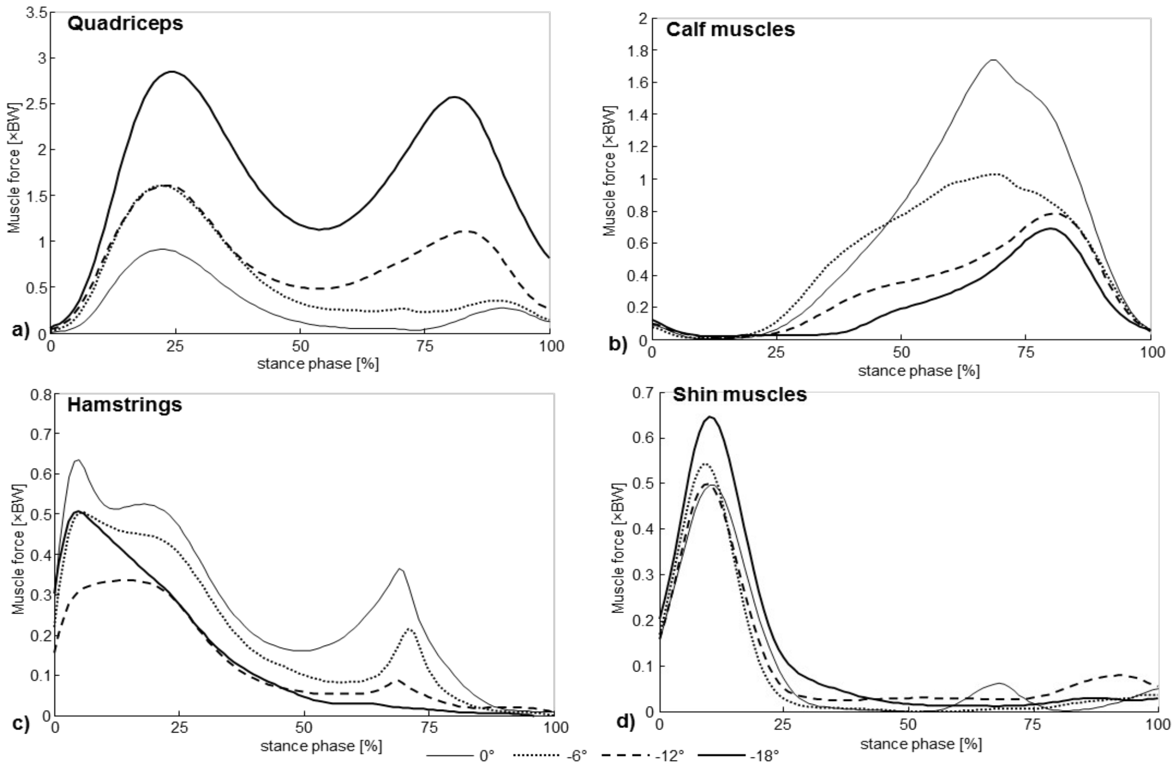

Figure 1: Muscle forces of quadriceps (a), calf muscles (b), hamstrings (c), and shin muscles (d) during stance phase in the constant condition.

Table 2: Average muscle forces (×BW) across stance phase.

condition	inclination	quadriceps	hamstrings	calf muscles	shin muscles
	0°	0.35 ± 0.24*2,3,4	0.28 ± 0.14	0.61 ± 0.30*4	0.10 ± 0.05
	-6° (2)	0.73 ± 0.45*4	0.22 ± 0.09	0.51 ± 0.21*4	0.11 ± 0.04
self-paced	*-12° (3)*	1.07 ± 0.70	0.15 ± 0.08*4	0.34 ± 0.20	0.12 ± 0.06
	-18° (4)	1.75 ± 0.35	0.20 ± 0.10	0.31 ± 0.17	0.09 ± 0.04
	0°	0.29 ± 0.20*2,3,4	0.28 ± 0.15*4	0.66 ± 0.34*3,4	0.10 ± 0.07
	-6° (2)	0.57 ± 0.32*4	0.21 ± 0.11*4	0.50 ± 0.28*4	0.09 ± 0.05
constant	*-12° (3)*	0.97 ± 0.80	0.14 ± 0.07	0.30 ± 0.21	0.11 ± 0.05
	-18° (4)	1.71 ± 0.82	0.15 ± 0.08	0.22 ± 0.11	0.13 ± 0.08

Values are means ± SD. * significant ($p < 0.05$) differences to the respective inclination.

DISCUSSION: Speed was kept constant in the corresponding condition. Furthermore, stride length and stride width remained the same between conditions over all inclinations. Only during level walking there was a difference of 4 cm between both conditions, however this was not significant. Therefore, differences in walking speed were not due to altered stride length or stride width. Step length was shown to affect lower extremity joint loading more than cadence does (Schwameder et al., 2005), and therefore it is important to know for further interpretations that stride length, which can be brought into relation with step length, remained the same between both conditions.
Muscle forces during level walking were in agreement with other studies (Reilly & Martens, 1972; Sanford, Williams, Zucker-Levin, & Mihalko, 2013). Quadriceps, hamstrings and calf muscle forces could be compared with the control group data of Sanford et al. (2013), who also computed muscle forces with the help of AnyBody, and data showed to be in good agreement. However, quadriceps muscle force was found to be lower at all inclinations compared to the data presented by Schwameder (2004), but changes in respect to inclination were similar. Significant differences in average muscle force in respect to different inclinations were found in both conditions for quadriceps, hamstrings and calf muscle groups

(Table 2) showing a significant increase in quadriceps muscle force and a significant decrease in calf muscle force with increasing inclination compared to level walking. Although not significant, higher quadriceps muscle forces occurred in the self-paced compared to the constant condition. Since significant difference between self-paced and constant speed were found, it can be assumed that higher quadriceps muscle forces occur due to higher walking speed. Furthermore, an increase of load, especially in the knee joint structure forces, as a function of increased speed was shown in the literature (Schwameder et al., 2005). Therefore, this might explain why no effect of speed on possible difference between conditions was found for the other muscle groups, even though Murray, Mollinger, Gardner, and Sepic (1984) showed that EMG activity decreased as walking speed decreased.
Muscle forces of hamstrings, quadriceps and calf muscles found in the current study can be correlated with hip, knee and ankle joint extension moments, respectively, presented in the literature (Lay et al., 2006). Muscles forces of the shin muscles can be correlated to EMG activity of m. tibialis anterior (Murray et al., 1984).

CONCLUSION: This study identified that quadriceps muscle forces increase and calf muscle forces decrease with increasing inclination compared to level walking. Furthermore, it has been shown that speed influences quadriceps muscle forces. Hamstrings, quadriceps and calf muscle forces can be correlated with hip, knee and ankle joint extension moments, respectively. Therefore, it can be concluded that forces of major muscle groups of the lower extremities can explain the resulting joint extension moments. Knowing that the model reveals feasible data, in future studies, muscle force data can be used to calculate joint forces, individual differences, or metabolic cost, amongst others to gather additional and more detailed information.

REFERENCES:

Bässler, R. (1997). *Freizeitsport in Österreich.* Wien.
Blake, R. L., & Ferguson, H. J. (1993). Walking and hiking injuries. A one year follow-up study. *Journal of the American Podiatric Medical Association, 83*(9), 499-503.
Erdemir, A., McLean, S., Herzog, W., & van den Bogert, A. J. (2007). Model-based estimation of muscle forces exerted during movements. *Clinical Biomechanics, 22*(2), 131-154.
Franz, J. R., & Kram, R. (2012). The effects of grade and speed on leg muscle activations during walking. *Gait & Posture, 35*(1), 143-147.
Grampp, J., Willson, J., & Kernozek, T. (2000). The plantar loading variations to uphill and downhill gradients during treadmill walking. *Foot & Ankle international, 21*(3), 227-231.
Kuster, M., Wood, G. A., Sakurai, S., & Blatter, G. (1994). Downhill walking: a stressful task for the anterior cruciate ligament? A biomechanical study with clinical implications. *Knee Surgery, Sports Traumatology, Arthroscopy, 2*(1), 2-7.
Lay, A. N., Hass, C. J., & Gregor, R. J. (2006). The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of Biomechanics, 39*(9), 1621-1628.
Lee, S. H., Seo, B. D., & Chung, S. M. (2013). The Effect of Walking Exercise on Physical Fitness and Serum Lipids in Obese Middle-aged Women: Pilot Study. *Journal of Physical Therapy Science, 25*(12), 1533-1536.
Leroux, A., Fung, J., & Barbeau, H. (2002). Postural adaptation to walking on inclined surfaces: I. Normal strategies. *Gait & Posture, 15*(1), 64-74.
McIntosh, A. S., Beatty, K. T., Dwan, L. N., & Vickers, D. R. (2006). Gait dynamics on an inclined walkway. *Journal of Biomechanics, 39*(13), 2491-2502.
Murray, M. P., Mollinger, L. A., Gardner, G. M., & Sepic, S. B. (1984). Kinematic and EMG patterns during slow, free, and fast walking. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society, 2*(3), 272-280.
Redfern, M.S., & DiPasquale, J. (1997). Biomechanics of descending ramps. *Gait & Posture, 6*, 119-125.
Reilly, D. T., & Martens, M. (1972). Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. *Acta Physiologica Scandinavia, 43*, 126-137.
Sanford, Brooke A., Williams, John L., Zucker-Levin, Audrey R., & Mihalko, William M. (2013). Tibiofemoral Joint Forces during the Stance Phase of Gait after ACL Reconstruction. *Open Journal of Biophysics, 03*(04), 277-284.
Schwameder, H. (2004). *Biomechanische Belastungsanalysen beim Berggehen*. Aachen: Meyer & Meyer.
Schwameder, H., Lindenhofer, E., & Müller, E. (2005). Effect of walking speed on lower extremity joint loading in graded ramp walking. *Sports Biomechanics, 4*(2), 227-243.