LOWER LIMB JOINT AND MUSCLE FORCES DURING SLOPED WALKING AT SELF-SELECTED SPEED

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The aim of this study was to analyse lower limb joint and muscle forces during level and sloped walking. Male participants (n=18, 27±5 y, 1.80±0.05 m, 75±8 kg) walked at self-selected speed at level and on a ramp (±18°). Joint and muscle forces were analysed using a musculoskeletal model. Downhill walking increased maximum tibiofemoral and patellofemoral compression forces and decreased ankle compression forces, while uphill walking increased all analysed lower limb joint forces. Muscle forces were altered during sloped walking. Amongst others, downhill walking increased quadriceps (>248%) and decreased gastrocnemii (<63%) muscle forces in comparison to level walking. Uphill walking increased mean quadriceps (>57%) and gastrocnemii (>40%) muscle forces. Results might be used for the development of rehabilitation and training procedures.

KEY WORDS: uphill, downhill, inverse dynamics, musculoskeletal modelling.

INTRODUCTION: Hiking is a popular sport in mountain regions and positive effects have been shown in several studies (Lee, Seo, & Chung, 2013). However, hiking 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). Sloped walking is associated with increases in lower extremity joint loadings compared to level walking (Lay, Hass, & Gregor, 2006). Downhill walking leads to large increases in knee extension moments with increasing inclination, while uphill walking increases hip extensor, knee extensor and ankle plantar flexor moments with increasing inclination (Lay et al., 2006). Joint moments, however, do not account for changes in muscle activation that may occur during sloped walking when compared to level walking and thus may not reflect the real joint loadings (Haight, Lerner, Board, & Browning, 2014; Lay et al., 2006). Furthermore, muscles have been shown to be the major contributors to the joint contact forces (Correa, Crossley, Kim, & Pandy, 2010; Valente, Taddei, & Jonkers, 2013). This motivates the analysis of joint and muscle forces during downhill and uphill walking.
Several studies analysed lower limb joint (Steele, Demers, Schwartz, & Delp, 2012) and muscle forces (Correa et al., 2010; Valente et al., 2013) using musculoskeletal models during level walking. In contrast, the number of studies investigating joint (Alexander & Schwameder, 2016b; Haight et al., 2014) and muscle forces (Dorn, Wang, Hicks, & Delp, 2015; Haight et al., 2014) during sloped walking is limited. Analysing joint forces during sloped walking revealed increased hip, tibiofemoral and patellofemoral compression forces and decreased compressive ankle forces during downhill walking, while uphill walking increased all analysed lower limb joint forces with increasing inclinations when walking at a pre-set speed of 4 km/h (Alexander & Schwameder, 2016b). In daily activities, however, speed is not prescribed and establishes the analysis of sloped walking at a self-selected speed for providing better evidence based training program recommendations.
Thus, the aim of this study was to analyse lower limb joint and muscle forces spanning the hip, tibiofemoral, patellofemoral and ankle joint during level, downhill and uphill walking.

METHODS: Eighteen healthy male participants (age: 27.0 ± 4.7 y, height: 1.80 ± 0.05 m, mass: 74.5 ± 8.2 kg) were recruited. The study was approved by the ethics board and informed consent was signed by all participants. Participants walked at a self-selected speed on a ramp at the inclination angles -18°, 0° and 18°. Reflective markers were attached to the participants. Kinematic data were captured with a 12-camera, marker based motion capture system (Vicon, Oxford, Oxford Metrics Ltd, UK; 250 Hz) and kinetic data were recorded with two force plates (AMTI, Advanced Mechanical Technology Inc., USA; 1000 Hz) embedded into the ramp.

Kinematic and kinetic data were filtered using a Butterworth low pass filter with 10 and 15 Hz cut off frequencies, respectively. A musculoskeletal model (AMMR 1.6.2, MoCapModel; vers.6.0, AnyBody Technology, Denmark) previously validated for sloped walking (Alexander & Schwameder, 2016a) was used to compute joint and muscle forces. Mean and maximum hip, tibiofemoral (TF), patellofemoral (PF) and ankle compressive forces were calculated as well as mean muscle forces of gluteus maximus (GLmax), medius (GLmed) and minimus (GLmin), piriformis (Piri), adductors (Add; sum of adductor longus, brevis and magnus, pectineus and gracilis), iliopsoas (IP), rectus femoris (RF), vastus medialis (VM), lateralis (VL) and intermedius (VI), biceps femoris (BF), semitendinosus (ST), semimembranosus (SM), gastrocnemius medialis (GM) and lateralis (GL), soleus (Sol), peroneus (Per) and tibialis anterior (TA). Joint and muscle forces were normalized to body weight (×BW) and time-normalized to gait cycle duration.
Statistical analysis ($\alpha = 0.05$) was conducted using SPSS (vers. 22.0, IBM, Armonk, NY, USA). Requirements for normality (Shapiro-Wilk) were only partly achieved. Therefore, changes in joint and muscle forces were analysed using the Friedman test. In cases of significance, Wilcoxon tests with Bonferroni correction ($\alpha = 0.017$) were used for pairwise post-hoc comparisons. Effect sizes for each comparison were quantified using Cohen's d_z to be small (d = 0.20-0.49), medium (d = 0.50-0.79) or large (d > 0.80) (Cohen, 1992).

RESULTS: Participants walked significantly slower downhill (1.12 m/s, $p = 0.012$, $d = 0.66$) and uphill (1.07 m/s, $p = 0.003$, $d = 0.83$) compared to level (1.24 m/s). Walking speed did not differ significantly between downhill and uphill walking ($p = 0.036$, $d = 0.54$).

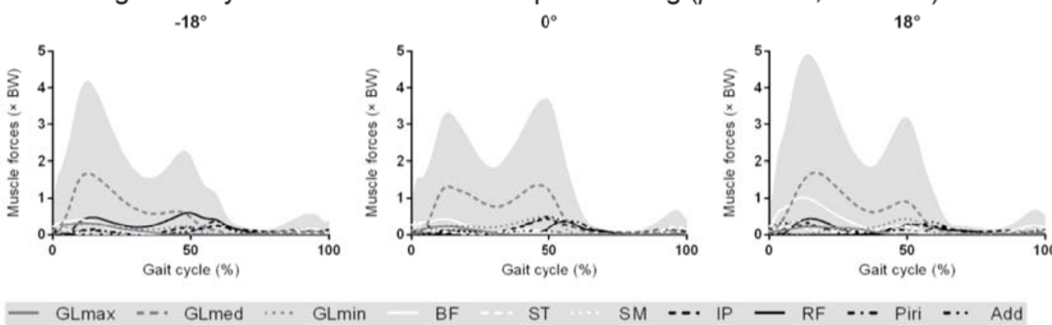

Figure 1: Hip compression force (grey area) and muscle forces during -18° downhill, level and 18° uphill walking.

The gait analysis revealed significant main effects of inclination ($p < 0.05$) on all mean and maximum joint forces and mean muscle forces. Downhill walking increased ($p < 0.017$) maximum TF ($d = 1.07$) and PF ($d = 3.33$) compression forces and decreased ankle compression forces ($d = 1.39$), while uphill walking increased ($p < 0.017$, $d > 1.07$) all lower limb joint forces. All joint forces were significantly lower during downhill compared to uphill walking, except mean PF forces, which were significantly higher.

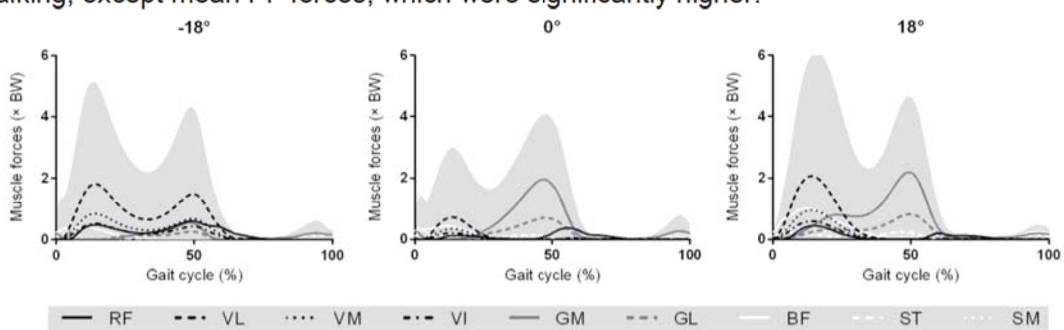

Figure 2: Tibiofemoral compression force (grey area) and muscle forces during -18° downhill, level and 18° uphill walking.

During downhill walking, muscle forces of GLmax (d = 1.70), quadriceps (d > 3.52), Sol (d = 1.91) and Per (d = 0.82) were increased (p < 0.017) compared to level walking, while all other muscle forces (except BF) were decreased (p < 0.017, d > 0.52). Uphill walking decreased (p < 0.017) GLmin (d = 0.83), IP (d = 0.66) and TA (d = 0.84) muscle forces, while hamstrings (d > 0.54), GLmax (d = 1.50), Piri (d = 1.55), RF (d = 0.69), vasti (d = 3.17), triceps surae (d = 1.06) and Per (d = 1.67) were increased (p < 0.017).

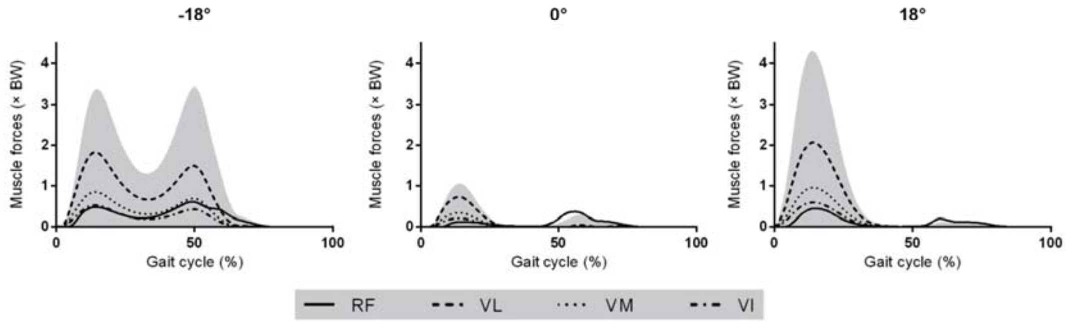

Figure 3: Patellofemoral compression force (grey area) and muscle forces during -18° downhill, level and 18° uphill walking.

GLmed forces were the highest among the hip-spanning muscles. Substantial increases of RF during downhill walking (248%) and BF during uphill walking (176%) have been observed (Figure 1). During level and uphill walking the gastrocnemii were the main active muscles in the second half of stance phase of the knee-spanning muscles. During uphill walking, quadriceps (>57%), BF (176%), ST (42%) and SM (74%) muscle forces increased. During downhill walking the quadriceps muscles were the most active ones (Figure 2). Over all conditions VL muscle forces were highest and RF was the only active quadriceps muscle during level walking in late stance (Figure 3). During downhill walking, Sol muscle forces were the highest of the ankle-spanning muscles. Uphill walking increased Sol (241%) and gastrocnemii (>40%) muscle forces compared to level walking (Figure 4).

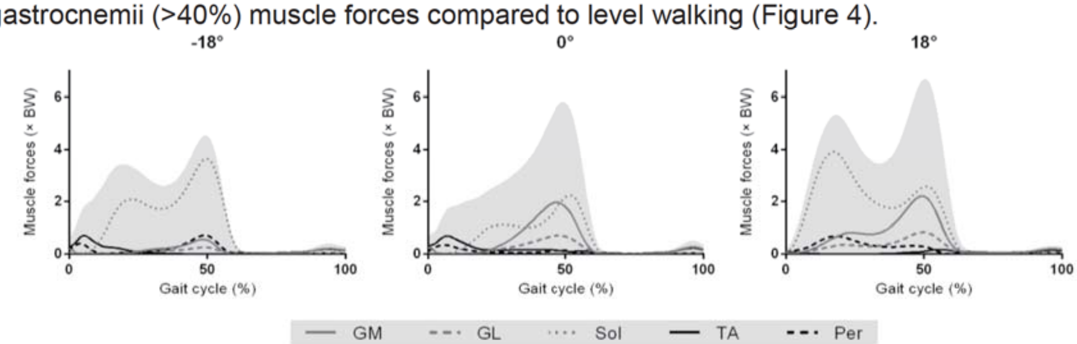

Figure 4: Ankle compression force (grey area) and muscle forces during -18° downhill, level and 18° uphill walking.

DISCUSSION: Sloped walking led to altered joint and muscle forces. Maximum compressive joint forces were between 3.9-4.8 ×BW, with the highest force observed in the ankle joint. Joint and muscle forces during level walking were consistent with data presented in previous studies (Correa et al., 2010; Valente et al., 2013). During sloped walking, muscle force patterns were similar to Haight et al. (2014), but the magnitudes could not be compared due to differing walking speeds. Furthermore, muscle force results did not entirely support results of a predictive simulation of uphill walking (Dorn et al., 2015). In agreement with Correa et al. (2010), gluteus medialis provided the greatest contribution to the compressive hip force. The crouched posture during sloped walking (Lay et al., 2006) is most likely responsible for the increased quadriceps force (Steele et al., 2012) and therefore the increased TF and PF joint loadings. During sloped walking PF joint forces exceeded 3 ×BW, which was found to be about the peak value in normal daily activities (Trepczynski, Kutzner, Kornaropoulos, Taylor, Duda, Bergmann et al., 2012).

Comparing maximum joint forces during sloped walking at a pre-set speed of 4 km/h (Alexander & Schwameder, 2016b) and the joint forces observed in the current study, following descriptive statements can be made: due to higher joint forces during level walking, hip compression forces were not significantly increased during downhill in comparison to level walking as was previously reported. Level: hip (6.6%), TF (3.3%), PF (24.5%) and ankle (13.8%) joint forces were increased at self-selected speed. Downhill: hip, TF and PF compression forces were decreased by 0.9-1.6%, while ankle forces were increased by 4.1% at self-selected speed. Uphill: self-selected speed increased hip (0.3%), TF (1.8%), PF (4.0%) and ankle (8.7%) forces. Besides changes in maximum forces, some alterations in the force patterns are visible during uphill walking at the TF joint (lower 2nd peak at self-selected speed) and both uphill and downhill walking at the ankle joint (alterations concerning the 1st peak). The comparison of maximum joint forces during downhill and uphill walking showed that joint forces were significantly lower at all joints during downhill walking at self-selected speed, while at a pre-set speed only hip, TF and ankle forces were decreased. Alterations in walking speed might be responsible for some of the differences, but can probably not account for all of them: e.g. self-selected walking speed was lower compared to pre-set speed, but joint forces were slightly increased. Furthermore, the effect of walking speed alterations is different at each joint. Finally, it can be assumed that muscle forces acting on the joints are also altered between walking speed conditions.

CONCLUSION: The effect of sloped walking on lower limb joint forces was similar at self-selected speed compared to pre-set speed previously reported in the literature. Concerning maximum forces uphill walking seems to be the more stressful task for the lower limb joints. This study provided important information on joint and muscle forces during sloped walking, which might be used for the development of rehabilitation and training procedures.

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