ENERGETICS OF THE LOWER EXTREMITY JOINTS DURING GRADED WALKING ON A SLOPE COMPARED WITH ASCENDING AND DESCENDING STAIRS

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The purpose of this study was to compare the energetics of the lower extremity joints during uphill and downhill walking on slopes and stairs. 10 subjects were filmed and their ground reaction forces were measured during uphill and downhill walking on a ramp and on a staircase (24°) at the same speed. Inverse dynamics were used to calculate net joint forces and moments as well as joint power and energy at the ankle, knee and hip joint. Both, for uphill and downhill walking, the energy is more balanced in the staircase compared with the ramp conditions. Ascending stairs shifts the energy from the ankle joint to the hip joint, while in descending stairs a shift from the knee joint to the ankle joint can be observed.

KEY WORDS: joint energy, uphill walking, downhill walking, stairs climbing

INTRODUCTION: Hiking and mountain climbing is one of the most favorite sports in Alpine regions. Positive effects on the cardiovascular and cardiopulmonary systems, as well as on active and passive structures of the locomotor system have been reported (LaCroix et al., 1996) and can be explained by the higher loads on these systems during uphill and downhill walking. The biopositive limit, however, may be exceeded by long and intensive descents. Indicators for this assumption are diverse pain symptoms and injuries in the lower extremity joints frequently reported by hikers after long term downhill walking. Especially the knee joint is negatively affected by this kind of locomotion. These observations can be explained by high knee joint loads in downhill walking. Kuster et al. (1995) reported significantly increased peak ground reaction forces (+38%), peak knee flexion moments (+117%) and peak knee power (+490%) during downhill walking at a decline of 11° compared to level walking. Schwameder et al. (2000) showed that the relative contribution of the energy absorbed by the knee joint structures increased with the declination of the slope. The energy absorbed by the knee joint during downhill walking at 24° was more than 70%. The rest was equally distributed to the ankle and hip joint. Another study showed that the knee joint structure forces substantially increased with the grade of the slope. The peak patellofemoral compression force in downhill walking at 24° was found to be more than 5 times compared to level walking (Schwameder et al., 2001).
Considering these aspects one may look for measures to reduce the high joint loads during graded walking. Hiking poles were found to be a useful tool to reduce knee joint structure forces during downhill walking (Schwameder et al., 1999). Walking on stairs is supposed to be another meaningful measure to reduce loading on the knee joint. There are indications in the literature that descending stairs causes less loads on the knee joint than walking downhill on a graded slope (Andriacchi et al., 1997, Schwameder et al., 2000). The data, however, are not directly comparable due to different methodological setups. Based on these considerations the purpose of this study is to determine the energetics of the lower extremity joints during walking on stairs and graded slopes comparatively. It is hypothesized that the energy distribution of ankle, knee and hip joint differs from graded slope to stairs walking.

METHODS: A special ramp and staircase was built for this investigation. The ramp (5.1 m long and 1.2 m wide) had an inclination of 24°. A force plate was integrated into the ramp to measure the ground reaction forces of one stance phase (Figure 1). Control measurements showed that the inclination of the force plate did not impair the accuracy of the measured data. The staircase consisted of 7 steps with a riser height of 14 cm and a tread of 31 cm. A force plate built the fourth step of the staircase (Figure 2).
10 subjects (7 male, 3 female, 27 ± 4 years, 70.8 ± 9.1 kg, 1.75 ± 0.08 m) were asked to ascend and decend the ramp and the staircase. To guarantee constant walking speed the subjects had to adjust their step frequency to a metronome (1.67 Hz). The step lengths in the staircase

conditions were given by the steps. In the ramp conditions the subjects had to place their feet on ramp landmarks indicating the same length as in the staircase conditions.

Figure 1 - Ramp setup with force plate.

Figure 2 - Staircase setup with force plate.

The ground reaction forces (F_x and F_z) and the a-p-moment (M_y) were measured with a force plate (AMTI) at 500 Hz. From this kinetic data the application point of force in anterior-posterior direction (a_x) was calculated. The locomotions in the sagittal plane were filmed with a video camera (Panasonic F15, 50 Hz) located perpedicular to the walking direction. 7 body landmarks of the right limbs (toe, ball, heel, ankle, knee, hip, shoulder) were digitized manually and filtered with a 2nd order, zero-lag Butterworth low-pass filter at 7 Hz (Challis, 1999). The two local coordinate systems were aligned and the two data sets were synchronized and time-normalized during the data analysis process. Standard inverse dynamic procedure was used to calculate sagittal planar net forces (F_j) and net moments (M_j) at the ankle, knee and hip joint. Mechanical joint power (P_j) was calculated by $P_j = M_j\ \omega_j$. The positive and negative work done by the muscles around each joint (W_j+, W_j-) was calculated by the time integral of the positive and negative parts of P_j during one stance phase.

RESULTS AND DISCUSSION: In the following description 'energy at a joint' means the resultant mechanical energy generated or absorbed by the muscles around this specific joint.
The energy generated (W#+) during both, uphill walking on a slope and ascending stairs, decreases continuously from the ankle to the hip joint. In ascending stairs the energy generated is more balanced between the three joints. This causes significantly less energy at the ankle joint and significantly more energy at the hip joint in ascending stairs (Table 1). Concerning the energy absorbed (W#-) a similar situation can be observed, even though the amount of energy absorbed is much less than the energy generated. Again, in both situations the values decrease from the ankle to the hip joint continuously and the energy is more balanced while ascending stairs compared to uphill walking on a slope. The differences are significant for the knee and the hip joint. The total energy (W#) at the three joints in uphill walking on a ramp and on stairs is comparatively shown in Figure 3. Uphill walking on a slope needs significantly more energy at the ankle joint and significantly less energy at the hip joint. There is no difference at the knee.

Table 1 Positive, Negative and Total Work at the Ankle, Knee and Hip Joint in Uphill Walking and Ascending Stairs

	Wa+	Wa-	Wa	Wk+	Wk-	Wk	Wh+	Wh-	Wh
ramp	0.76	-0.20	0.56	0.52	-0.04	0.48	0.37	-0.03	0.33
stairs	0.63	-0.18	0.45	0.58	-0.10	0.48	0.50	-0.08	0.42
p(t)	0.03		0.03		0.02		0.00	0.00	0.02

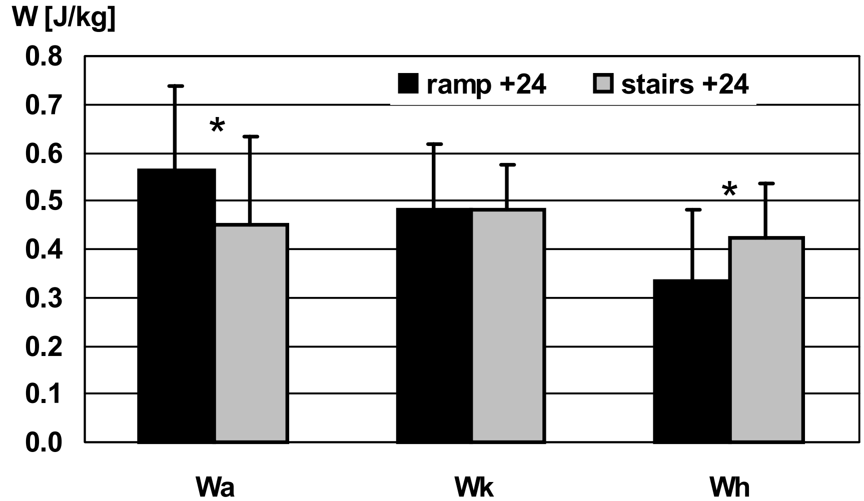

Figure 3 - Total work (energy) at the ankle, knee and hip joint in uphill walking and ascending stairs.

Due to the restricted flexibility in the ankle joint uphill walking on a ramp with this specific inclination is performed by placing the foot on the ball. Therefore the whole locomotion of uphill walking and ascending stairs is similar. In the ramp situation, however, the body weight causes a more pronounced dorsiflexion in the first part of stance phase which has to be compensated by generating more energy with the plantar flexors in the second part of stance phase. This explains the higher positive and negative energy contribution of the ankle joint during ramp uphill walking. Placing the foot on the ball during the entire stance phase causes greater moment arms of force with respect to the ankle joint in this phase and enhances the energy generation at the ankle joint.

During downhill walking, both on a slope and on stairs, the energy generated in all joints is small (Table 2). The amount of energy generated, however, is higher at all three joints during descending stairs. The differences are significant for the ankle and the hip joint. The highest contribution of energy absorption during downhill walking is observed at the knee joint. The amount of energy absorbed in descending stairs is significantly higher at the ankle joint and significantly reduced at the knee joint.

Table 2 Positive, Negative and Total Work at the Ankle, Knee and Hip Joint in Downhill Walking and Descending Stairs

	Wa+	Wa-	Wa	Wk+	Wk-	Wk	Wh+	Wh-	Wh
ramp	0.08	-0.28	-0.20	0.03	-1.15	-1.12	0.04	-0.12	-0.08
stairs	0.14	-0.68	-0.54	0.11	-0.95	-0.84	0.10	-0.12	-0.02
p(t)	0.01	0.00	0.00		0.03	0.00	0.01		0.00

The total energy differs between downhill walking on a slope and descending stairs at all three joints significantly. Descending stairs needs more energy absorption at the ankle joint and less at the knee and the hip joint (Figure 4).

The major difference in walking downhill on a slope and on stairs is the position of the foot on the ground. Descending stairs causes a more pronounced dorsi flexion during stance phase. This causes a stronger push-off from the stairs which explains the greater energy generation at all three joint. The restricted flexibility of the ankle joint causes a faster movement of the application point in anterior direction during second stance. This causes higher energy absorption of the plantar flexors and less energy absorption of the knee extensors.

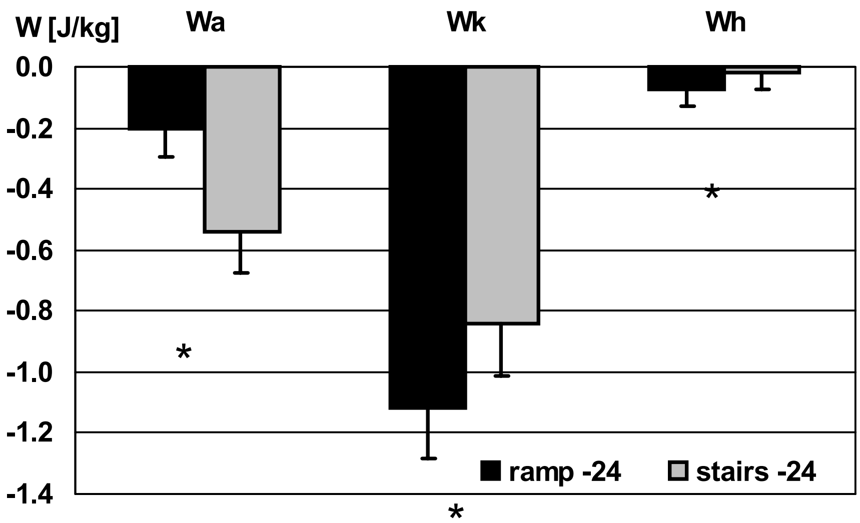

Figure 4 - Total work (energy) at the ankle, knee and hip joint in downhill walking and descending stairs.

CONCLUSION: The comparison of slope walking and stairs climbing with respect to energy aspects of the lower extremity joints showed that both, in uphill and downhill walking, the energy distribution between the three joints is more balanced in ascending and descending stairs than in the comparable situations on the slope. For walking uphill a shift of energy generation from the plantar flexors of the ankle joint to the hip extensors has been observed. This energy transfer can be effectively used either to prevent the plantar flexors from overuse during long ascents (e.g. in mountain climing) by using stairs as often as possible or to exercise this muscle group specificly by walking uphill on steep slopes. Similar recommendations can be given for downhill walking where in descending stairs a shift of energy absorption from the knee extensors to the plantar flexors has been found compared to slope walking. To prevent the knee extensors from high eccentric loadings and high energy absorption stairs should be used whenever possible while walking downhill. An athlete who wants to stimulate this muscle group with specific eccentric loadings should walk or run on slopes preferably than on stairs.

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