KNEE JOINT LOADING IN GRADED WALKING AS A FUNCTION OF STEP LENGTH AND STEP FREQUENCY

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The purpose of this study was to determine the knee joint loading during uphill and downhill walking as a function of step length and step frequency. Twelve subjects were filmed and their ground reaction forces measured during uphill and downhill walking on a ramp at 18° to the horizontal at step lengths of 46, 58 and 69 cm and step frequencies of 1.33, 1.67 and 2.00 Hz, respectively. 2D inverse dynamics were used to calculate knee joint forces, moments and power. In general, knee joint loading increases with both longer steps and higher step frequencies. Most of the differences are statistically significant. The results show that step length and step frequency affects knee joint loading significantly and substantially. Thus knee joint loading can be controlled by regulating these two parameters. This is important when trying to optimise the stimulation of knee joint structures.

KEY WORDS: knee joint loading, knee joint forces, uphill walking, downhill walking, step length, step frequency.

INTRODUCTION: Graded walking over extended periods of time typically occurs during hiking and mountaineering. The positive effects of these sports on the cardiovascular and cardiopulmonary systems, as well as on the active and passive structures of the locomotor system are well known and have been well documented in the literature (LaCroix et al., 1996). 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 as frequently reported by hikers after long term downhill walking. Recently collected, non published data on 440 hikers show that almost 50% suffer from pain during or after hiking tours. The problems primarily occur during downhill walking and are most frequently located at the knee joint. These observations are in line with the results showing increased loading in downhill compared with level walking (Kuster et al., 1995; Schwameder et al., 2000; Schwameder et al., 2001). It has been shown that the knee joint loading is highly influenced by the gradient so that knee loading can be controlled by regulating this parameter. This seems to be particularly important for hikers with knee joint problems and for preventive reasons. Presumably, the change of stride length (SL) and step frequency (SF) affects knee joint loading as well. This has been documented by Collins & Whittle (1989) and Kirtley et al. (1985) with respect to walking speed. Martin & Marsh (1992) found effects on ground reaction forces by changing step length and step frequency during level walking. Graded walking has not been studied concerning these aspects yet. This information, however, would be helpful in assessing if and how knee joint loading can be influenced and controlled by step length and step frequency, thus enabling knee joint structures to be optimally stimulated without overloading. Based on these considerations the purpose of this study was to determine the net knee joint forces, moments and power during graded walking as a function of step length and step frequency. It was hypothesized that knee joint loading increases with both step length and step frequency. Furthermore, it should be determined how sensitively knee joint loading reacts to changes in these parameters which is most likely to be related to knee pain and knee injuries.

METHODS: A special ramp (5.1 x 1.2 m) inclined at 18° to the horizontal was built for this study. A force plate was integrated into the ramp to measure the ground reaction forces and moments during one stance phase (Figure 1). Control measurements showed that the inclination of the force plate did not influence the accuracy of the data. Twelve subjects (8 male, 4 female, 24 ± 2 yrs, 71.7 ± 8.2 kg, 1.73 ± 0.06 m) were asked to walk the ramp uphill and downhill at the following nine conditions: step lengths 46, 58, 69 cm with step frequencies of 1.33, 1.67 and 2.00 Hz respectively. The step lengths were indicated by markers on the ramp. The subjects were required to try out each step length and step frequency long enough to ensure a comfortable and natural walking pattern as possible. The ground reaction forces (F_x and F_z) and the anterior-posterior moment (M_y) were measured with a force plate (AMTI) at 500 Hz. From this kinetic data the application point of force in the anterior-posterior direction (a_x) was determined. The locomotion in the sagittal plane was filmed with a digital video camera (JVC 9330, 60 Hz) which was located in the perpendicular to the walking direction. 7 body landmarks of the right limbs (toe, ball, heel, ankle, knee, hip, shoulder) were digitized automatically and in some cases manually using SIMI Motion software. The data was filtered with a 2^{nd} 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 procedures were used to calculate the sagittal planar net forces (F_k) and net moments (M_k) at the knee joint. The mechanical knee joint power (P_k) was calculated by $P_k = M_k\ \omega_k$. The data was statistically analysed using a two-factorial (SL, SF) ANOVA approach.

Figure 1. Ramp with integrated force plate.

RESULTS: Table 1 shows the group means (and standard deviations) of the peak resultant knee joint forces (Fk), knee moments (Mk) and knee power (Pk) in graded uphill and downhill walking as a function of step length and step frequency respectively. Peak net knee joint forces, moments and power increase significantly with both step length and step frequency.

Table 1 . Peak resultant knee joint forces, peak knee moments and peak power in uphill and downhill walking as a function of step length and step frequency.

	uphill			**downhill**		
Fk [N/kg]	**slow**	**middle**	**fast**	**slow**	**middle**	**Fast**
short	9.4 (0.3)	9.4 (0.3)	9.5 (0.3)	10.8 (0.5)	12.4 (0.8)	12.8 (0.8)
middle	9.7 (0.4)	10.1 (0.4)	10.5 (0.5)	11.9 (0.7)	13.9 (0.8)	15.0 (1.0)
long	10.2 (0.4)	10.9 (0.6)	11.3 (0.6)	15.0 (0.9)	16.0 (0.9)	17.0 (1.2)
Mk [Nm/kg]						
short	0.5 (0.0)	0.5 (0.1)	0.7 (0.1)	0.9 (0.2)	1.3 (0.2)	1.3 (0.2)
middle	0.7 (0.1)	0.9 (0.2)	0.9 (0.2)	1.2 (0.2)	1.5 (0.2)	1.8 (0.3)
long	1.0 (0.2)	1.2 (0.2)	1.2 (0.2)	1.7 (0.3)	1.8 (0.3)	2.1 (0.4)
Pk [W/kg]						
short	0.8 (0.1)	0.9 (0.1)	1.1 (0.1)	-1.5 (0.2)	-2.5 (0.4)	-2.8 (0.4)
middle	1.3 (0.2)	1.7 (0.2)	1.8 (0.2)	-3.1 (0.5)	-4.6 (0.6)	-5.8 (0.7)
long	1.9 (0.4)	2.5 (0.4)	2.5 (0.4)	-5.5 (0.7)	-6.0 (0.7)	-8.5 (0.9)

For the moments and the power all and for the forces most of the differences are significant. The forces had the lowest effect whilst the knee joint power had the most pronounced effect. This is valid for both uphill and downhill walking. Under the same conditions (SL, SF) all loading parameters are higher for downhill than for uphill walking. In addition, the effects of step length and step frequency are more pronounced for downhill than for uphill walking (up to a factor of 3). Furthermore, all loading parameters are more affected by the step length than by the step frequency (up to a factor of 3). The time histories of the knee joint power for different conditions are presented in Figure 2. For uphill walking and under all conditions power is generated by the knee extensors primarily over the first half of the stance phase. The power generated, however, depends substantially on the step frequency and the step length. The peak values are particularly affected by these conditions. The graphs also show that the step length affects knee power to a much higher extent than the step frequency. The power absorption in the knee joint structures during downhill walking is more pronounced over the first and the last third of the stance phase. As before, the step length and the step frequency affect knee power absorption substantially with the step length being the most dominant factor.

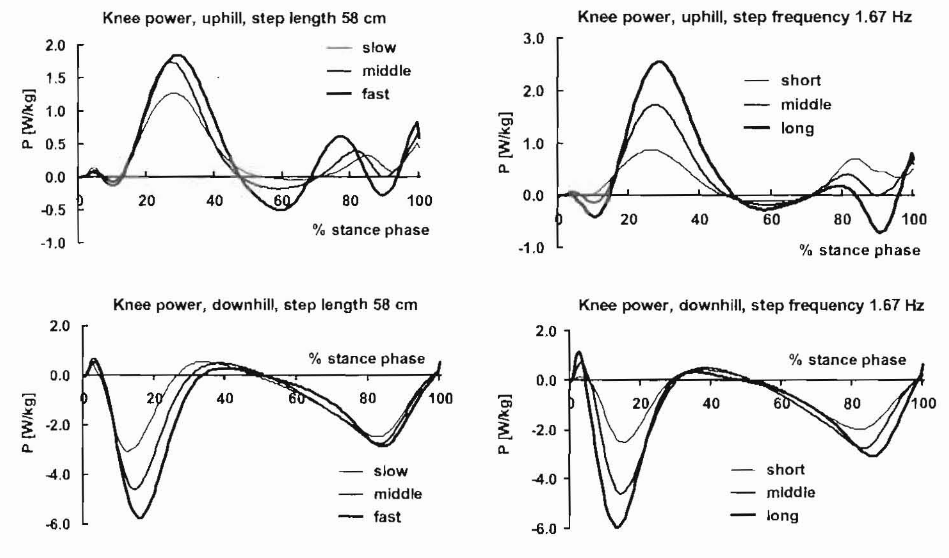

Figure 2. Time histories of the knee joint power in uphill walking (first row) and downhill walking (second row) as a function of step frequency (left column) and the step length (right column).

DISCUSSION AND CONCLUSION: Walking speed can be regulated by changing either the step length or the step frequency or by simultaneously changing both. It has been documented that the increase of walking speed affects the range of the knee angles (Kirtley et al., 1985), ground reactions forces (Martin & Marsh, 1992; Cook et al., 1997), horizontal and vertical impulses (Martin & Marsh, 1992), knee flexion moments (Kirtley et al., 1985), lumbosacral joint force distributions (Cheng et al., 1998) and the loads on the musculoskeletal system in general (Voloshin, 2000). Insofar that they are comparable, these findings are corroborated by the results of the study presented here. Furthermore, the results show that both the step length and the step frequency, affect knee joint loading significantly. The data clearly shows that the step length is the dominant factor concerning this aspect and therefore serves as the more sensitive control parameter of knee joint loading. Based on these observations, it can be concluded that knee joint loading is affected by both these walking speed determining parameters. The practical application of these results is obvious. Knee joint loading during graded walking as one of the main causes of knee pain and injuries can be reduced by reducing the step length and/or the step frequency whereby, however, the step length is the dominant factor. The highest reduction in knee joint loading can be achieved by lowering both components simultaneously. This applies to uphill and downhill walking in the same manner. Corresponding recommendations can be given to hikers who generally want to prevent overloading of their knee joint or, in particular, to those with knee joint problems. It can be concluded that step length and step frequency are meaningful aids in regulating knee joint loading during graded walking. The results of this study can serve as a basis for rehabilitation programs for knee injuries, for walking strategies in preventing or avoiding knee pain or for the development of specific training programs for hikers. Although the effects of step length and step frequency on knee joint loading are substantial, further investigation is necessary in order to determine the biological effects of the specific stimulations caused by varying these two parameters. One of the next steps in this direction would be the analysis of particular knee joint structure forces using an adequate knee model.

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