DIFFERENCES BETWEEN FORCES MEASURED VIA 1D PRESSURE INSOLES AND 3D FORCE PLATES DURING DOWNHILL GAIT

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A force measurement system independent of the lab is needed for field measurements of downhill gait. Therefore the forces of a pressure insole system (loadsol®) and the resultant force of a force plate (AMTI) were collected simultaneously during level and downhill gait (0°, -6°, -12° and -18°) and statistically compared using an ANOVA with repeated measurements and ICC. Peak forces during loading response and terminal stance and minimum force at mid stance showed significant main effects for the system, the inclinations and the interaction between both, with ICC between 0.68-0.96. Stance time showed a significant system and inclination effect, with ICC values between 0.26- 52. The loadsol® force parameters systematically overestimate the resultant force data (except Fmax1 in 0°) between 2-15%, and stance time between 8-10%.

KEYWORDS: pressure insoles, downhill gait, kinetics

INTRODUCTION: Uphill and downhill walking is an activity of daily living, but also a popular leisure activity in mountain regions. Sloped walking increases lower limb muscle forces (Alexander & Schwameder, 2016a), lower limb joint forces (Alexander & Schwameder, 2016b), internal loading of lower limb joints, especially of the knee joint (Schwameder, 2004) and muscle activity (Franz & Kram, 2012) compared with level walking. Commonly, studies investigating sloped gait have been carried out in laboratory set-ups with one or two force plates integrated in a ramp construction. This allows for high standardization, however, the participants are limited in the gait pattern, due to the length of the ramp construction and the need for accurate foot placement on the force plate. Therefore, alternative measurement systems, which do not constrain the participants, are needed. Using pressure insoles could be a potential solution, since no constraint on foot placement exists, to measuring several strides during gait (Cordero, Koopman, & Van Der Helm, 2004) and the data collection is independent of the lab (Crea, Donati, De Rossi, Oddo, & Vitiello, 2014). Thereby providing an opportunity for field measurements. Pressure insoles measure in one dimension (1D), and the calculated force could be called the “normal” force with respect to the sole. This, however, is not necessarily comparable with the vertical ground reaction force gained by three dimensional (3D) force plates. Particularly, at the heel-strike and toe-off events of the gait the force vector measured by pressure insoles could differ from the vertical force vector measured by a force plate. This difference results from the orientation of the sensors in the insoles (Hurkmans et al., 2006). During level walking and running the accuracy and repeatability of pressure insoles has been confirmed (Barnett, Cunningham, & West, 2001; Healy, Burgess-Walker, Naemi, & Chockalingam, 2012; Hurkmans et al., 2006; Martínez-Nova, Cuevas-García, Pascual-Huerta, & Sánchez-Rodríguez, 2007; Putti, Arnold, Cochrane, & Abboud, 2007). In downhill gait however, the gradient of the slope might influence the comparability of the 1D measured pressure insole force and the resultant force measured via a (3D) force plate (Figure 1).

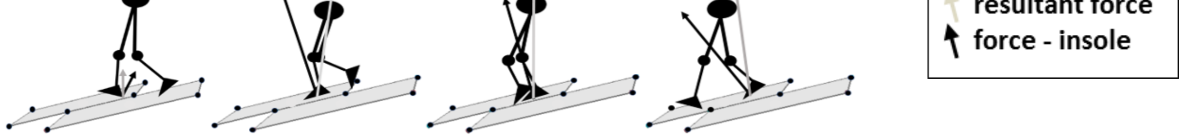

Figure 1: Schematic drawing of the resultant force and the 1D-loadsol force during downhill gait at -18°.

Therefore, the aim of this study was to compare the force accuracy during gait in different downhill inclinations when measured by a 1D pressure insole system and a 3D force plate. The findings are relevant to rehabilitation, elite and leisure hiking and mountaineering, given that a vertical ground reaction force system, such as the pressure insoles, could be practical and useful for monitoring lower extremity loading.

METHODS: 14 healthy (5 female, 9 male) participants (Mean ± SD of age: 25.5 ± 2 years; 1.76 ± 0.06 m; 68.4 ± 8.1 kg) were asked to walk on a ramp (6 x 1.4 m) with two integrated force plates (AMTI, Advanced Mechanical Technology Inc., Watertown, MA, USA, 1000 Hz), at four different inclination angles (0°, -6°, -12° and -18°). Simultaneously, the pressure insoles "loadsol®" (former Pedoped, Novel GmbH, Munich, Germany, 100 Hz) were placed in the shoes (Adidas, Duramo). Participants performed three successful trials at a constant, pre-set speed of 1.1 ± 0.03 m/s (4.0 ± 0.1 km/h). Speed was controlled via a timing device (Brower, Brower Timing Systems, Draper, UT, USA). For both systems the step on the force plate (step four) was used for further analysis. Out of 42 trials, three trials were removed due to system errors, resulting in a data set of 39 trials. The AMTI force plate was assumed to be the gold standard for force and temporal variables of gait analysis in this study. With a Matlab routine the insole data was up-sampled to 1000 Hz and data of both systems were imported into Visual 3D software (C-motion, Rockville, MD, USA). To detect differences between the systems, the force-time series of the absolute resultant force (F_{res}) and the absolute 1D force calculated from the loadsol® system were compared, as well as the following parameters: peak loading response (F_{max1}), minimum force at mid stance (F_{min}), peak force at terminal stance (F_{max2}) and stance time. The stance phase was identified for each system via a force threshold of 20 N. For all inclinations, the differences between the force plate and insole system for each parameter were compared using repeated measures ANOVA. The main factors were inclination angle and measurement system. For significant effects, post-hoc tests using t-tests were conducted. To detect a systematic under- or overestimation of the loadsol® system the intra-class correlation coefficient (ICC) was calculated independently for each inclination. The level of significance was set to $p < 0.05$ for all statistical methods.

RESULTS: The averaged results of both systems and the statistical analysis (main effects ANOVA, post-hoc t-tests and system ICC for each inclination) are presented in Table 1 and Figure 2. All main effects (inclination, measurement system and interaction) were significant ($p < 0.05$), except the interaction effect for stance time ($p = 0.323$). For all variables in all inclinations loadsol® systematically overestimated the force plate data, except for the F_{max1} in level walking (-32 ± 52N) (Figure 2). The loadsol® measured significantly higher values for the loading response peak (24 – 80 N), the midstance minimum (14 - 61 N) and the terminal stance peak (19 - 42 N). The overestimation of stance time of the loadsol® was between 0.06 and 0.07 s. In both systems, the F_{max1} values increase and the F_{max2}, F_{min} and stance time values decrease with increasing downhill inclination. The interaction effect between system and inclination shows that for the F_{max1} and F_{min} the absolute differences increase with increasing inclination, while for the F_{max2} the level and -18° condition show the highest absolute differences, which are significant when compared to the -12° (level) and -6° and -12° (for -18°) inclinations (Figure 2).

DISCUSSION: For F_{max1} and F_{min} the absolute differences between the two systems increase with increasing inclination, while some unsystematic differences occur for F_{max2}. With the exception of stance time, the high to very high ICCs (Table 1) between the two systems with values between 0.68 - 0.96 indicates a high systematic correlation for all inclinations. As such, when calculated in relative terms, the loadsol® 1D force for the peak loading response is an average of 4% lower at level walking and 3 – 9% higher during downhill walking compared to the resultant force of the 3D force plate. Further, on average the mid stance minimum and the terminal stance peak are 2 – 15% and 3 – 8% higher, respectively, when measuring with loadsol®. These differences in level walking and downhill gait are lower than the differences reported by Stöggl and Martiner (2017), who compared a different insole system during level walking and jumping (Moticon compared to force plate: 13-36% lower impulse).

Table 1: Comparison of force and temporal variables for level and downhill inclinations

	AMTI	loadsol®	ANOVA		*System[b]	
	Mean ± SD	Mean ± SD	Main effects	η^2	Sig.	ICC
F_{max1} [N]						
0°	738 ± 91.7	707 ± 75.8	<.001[a]	.28[a]	<.001*	0.81
-6°	860 ± 124.3	883 ± 116.7	<.001[b]	.83[b]	<.001*	0.96
-12°	936 ± 149.7	990 ± 146.8	<.001[c]	.57[c]	<.001*	0.92
-18°	1006 ± 193.4	1087 ± 183.9			.001*	0.89
F_{max2} (N)						
0°	749 ± 86.7	788 ± 114.5	<.001[a]	.38[a]	<.001*	0.88
-6°	665 ± 73.6	685 ± 101.3	<.001[b]	.67[b]	.085	0.72
-12°	613 ± 61.0	636 ± 77.1	.035[c]	.07[c]	.001*	0.83
-18°	581 ± 81.9	624 ± 83.5			<.001*	0.81
F_{min} (N)						
0°	56 ± 79.2	576 ± 89.2	<.001[a]	.60[a]	.032*	0.90
-6°	518 ± 69.4	540 ± 97.9	<.001[b]	.70[b]	.056	0.68
-12°	464 ± 64.3	500 ± 70.7	<.001[c]	.20[c]	<.001*	0.93
-18°	410 ± 56.8	471 ± 73.7			<.001*	0.86
Stance time (s)						
0°	0.76 ± 0.04	0.83 ± 0.09	<.001[a]	.51[a]	<.001*	0.26
-6°	0.73 ± 0.05	0.80 ± 0.08	<.001[b]	.59[b]	<.001*	0.28
-12°	0.69 ± 0.05	0.76 ± 0.08	.323[c]	.03[c]	<.001*	0.39
-18°	0.67 ± 0.05	0.73 ± 0.09			<.001*	0.52

[a] Results of ANOVA for main factor inclination. [b] Results of ANOVA for main factor measurement system. [c] Results of ANOVA for main factor interaction. *indicates significant difference for system comparison

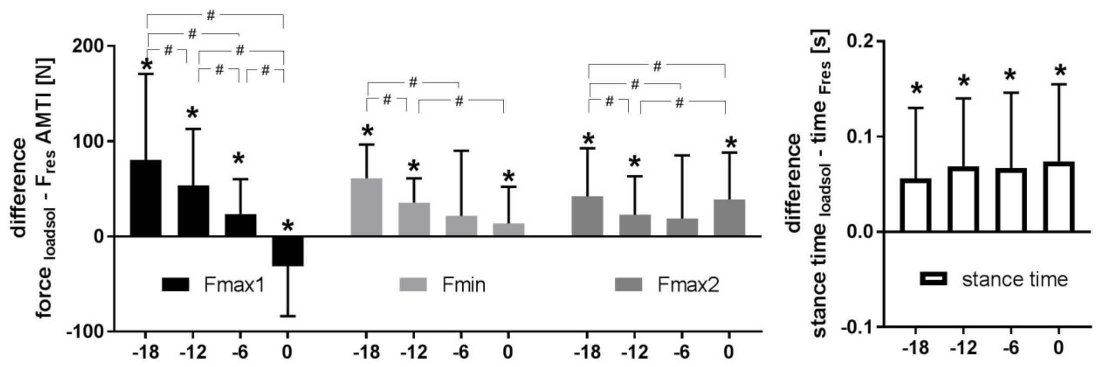

Figure 2: Mean absolute differences between loadsol® and AMTI force plate (calculated: loadsol® data minus AMTI force plate data). * indicates significant system effect in each inclination, #: significant interaction effect between system.

The high standard deviations of all variables can be explained by the methodological approach of using absolute forces as opposed to e.g. weight normalized forces. The higher the measured forces, the greater the discrepancy between the systems for the F_{max1} variable was. This might be attributed to the differences in the response of the capacitive sensors of the loadsol® system. Stöggl and Martiner (2017) and Barnett et al. (2001) speculated for the Moticon insole system that the latency in the rise or fall of the measured forces influences the accuracy of the measured data over the stance phase leading to more accurate data later in stance. However, the similar differences in F_{max1} and F_{max2} in this study do not support this explanation for the loadsol® system. Different results are shown for the variable stance time, which show a systematic overestimation of the insole system between 8 – 10% for all inclinations, with ICC values between (.26 - .52). The longer latency time of the loadsol® system could explain this, which is in agreement with the findings of Stöggl and Martiner (2017). The difference appears to be a systematic effect as it is independent of the inclination angle and the magnitude of the force. It's important to note that the forces compared in this study might not necessarily be similar in orientation and magnitude (Figure 1), as they represent two different force components: 1) the "normal" vector of the insole system and 2) the resultant force of the 3D force plate. The present study shows that increasing the inclination of the walking surface leads to increases of these differences. This limitation seems to be systematic and the high ICC for the kinetic data suggests, that the pressure insole system responds similarly to changes in force amplitude when compared to a force plate. The force-time characteristic of the signals should be investigated further to determine to what extend the loadsol® system can be used in the field to analyze downhill gait.

CONCLUSION: The loadsol® system systematically overestimated the resultant force and stance time during inclined walking on a 3D force plate. The angle of inclination had a significant effect on the amount of absolute overestimation, however, the relative differences demonstrated good agreement with the resultant force. Therefore, the loadsol® insoles could possibly be used to detect intersubjective changes in gait analysis of graded walking for rehabilitation, elite and leisure hiking/mountaineering, however comparison to resultant force should be made with caution and with keeping these differences in mind.

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