VALIDATION OF AN IMU-SYSTEM (GAIT-UP) TO IDENTIFY GAIT PARAMETERS IN NORMAL AND INDUCED LIMPING WALKING CONDITIONS

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The purpose of this study was to investigate an IMU system (GaitUp) with respect to validity in normal and induced impaired walking by comparing with a state-of-the-art 3D motion capture system. The gait of nine participants was analysed collecting data simultaneously with the GaitUp (Physiolog) placed at each foot and an eight camera motion capture system (Vicon) at 200 Hz each. Participants walked in normal and induced limping (elevation of one shoe) conditions at three walking speeds. For all conditions the two systems yielded similar results regarding the standard gait parameters (gait cycle time, stride length, stride frequency and gait velocity) according to absolute differences and correlation coefficients. GaitUp gathers fairly valid and reliable data in normal and limping walking in a range of walking speed between 0.9 and 2.0 m/s.

KEY WORDS: IMU, gait analysis, gait parameters, limping.

INTRODUCTION: The ability to walk is a key aspect in daily living. Therefore, the analysis of the gait pattern is often used as a tool to diagnose functional impairment or to evaluate a therapy program. Numerous methods exist ranging from qualitative observation by the therapist, or by the number of meters accomplished in a certain time up to more detailed methods taking also into account kinematic, kinetics and/or muscle activity of the gait. In the clinical and therapeutic setting often the time and equipment (e.g. cameras and force plates) are not available for a detailed gait analysis and the need for a system providing quick and valid data in a simple way is apparent. The introduction of inertial measurement unit (IMU) sensors combining accelerometers and gyroscopes provide a possible tool for clinicians to measure kinematic gait parameters over multiple steps in a daily routine. The data processing of IMU sensors, however, bears some difficulties and the feasibility of using these tools on a wide basis needs to be coupled with an analysis tool for automatically processing the measured data. As the user generally cannot interfere in these customised systems, it is important to analyse the validity of the automatically calculated parameters. Furthermore, patients usually do not display a normal gait pattern, but might show limping or asymmetric locomotion. Hence, the system should be able to identify cycle internal variations in walking velocity or the effect of shoe-characteristics on spatio-temporal variables. GaitUp (Lausanne, Switzerland) developed a gait analysis package including a sensor for each foot and analysis software with an implemented algorithm to detect 3D gait parameters (Mariani, Hoskovec, Rochat, Bula, Penders & Aminian, 2010; Mariani, Rochat, Büla & Aminian, 2012; Mariani, Rouhani, Crevoisier & Aminian, 2013). The system has been already validated in young and elderly individuals (Mariani et al. 2010, Mariani et al. 2012, Mariani et al. 2013, Brégou Bourgeois, Mariani, Aminian, Zambelli & Newman 2013). The purpose of this study was to investigate the GaitUp system with respect to validity in normal and induced impaired walking by comparing with a state-of-the-art 3D motion capture system.

METHODS: The gait of nine participants was analysed collecting data simultaneously with the Physiolog sensors (Physiolog4, GaitUp System, Lausanne, Sitzerland, 200 Hz) placed at each foot with a Velcro strap and an eight camera motion capture system (Vicon, Oxford Metrics, Oxford, UK, 200 Hz). Additionally, two force plates (AMTI, 1000 Hz) imbedded in the walkway were used to identify the time of heel-strike and toe-off. Participants walked in normal and induced limping conditions. For the normal condition a custom training shoe was worn on both feet. To induce a limping mechanism, a modified shoe with a sole thickness of +2.5 cm was put on the right foot instead of the regular shoe (Figure 1). For simultaneous analysis the Gait-Up Sensor Physiolog4 was adjusted at the foot according to the instructors guidelines and reflective markers were placed at each shoe (1st, 2nd and 5th metatarsal joint, heel) and both ankles (medial and lateral condyles) of the participants (Figure 2).


Figure 1: Modified shoe inducing limping


Figure 2:Placement of Physiolog4 and markers

Testing consisted of walking in normal condition (shoe sole the same height) and the limp condition (right shoe with increased sole thickness) for each self-selected slow, medium and fast velocity. For each condition one left and one right step placed on the force plate were identified using a video system (Panasonic). Five representative parameters of these steps automatically calculated by the GaitUp software were comparatively analysed with the same parameters calculated with V3D using from the motion capture data: gait-cycle time [s], stride length [m], stride frequency [stride/min], gait velocity [m/s] and foot angle at heel-strike [°]. Statistic calculations yielded absolute differences and Pearson's correlation coefficients for comparing the two corresponding data sets for each setting and parameters of interest. Blant-Altman plots were used to visualise the amount and tendency of the system deviations for the different conditions. Data analysis has been performed for the right limb only.

RESULTS: Tables 1 and 2 display the mean (SD) values of the selected gait parameters measured with GaitUp (GU) and Vicon (VI) as well as the mean of the absolute differences (ab-diff) between the two measurement systems in the normal (Table 1) and induced limping condition (Table 2) for slow, neutral and fast walking speed.

Table 1: Gait parameters (means, SD in brackets) measured with GaitUp (GU) and Vicon (VI) in normal walking condition with slow (s), neutral (n) and fast (f) walking speed and absolute differences between the systems (ab-diff, mean), right leg, n=9

parameter (normal)	*GU-s*	*VI-s*	*ab-diff*	*GU-n*	*VI-n*	*ab-diff*	*GU-f*	*VI-f*	*ab-diff*
gait cycle time [s]	1.263 (.016)	1.269 (.114)	0.008 (.012)	1.101 (.065)	1.111 (.066)	0.020 (.019)	0.982 (.055)	0.985 (.053)	0.008 (.005)
stride length [m]	1.383 (.103)	1.375 (.095)	0.014 (.008)	1.513 (.144)	1.519 (.140)	0.017 (.017)	1.713 (.128)	1.757 (.145)	0.043 (.035)
stride frequency [min^{-1}]	95.6 (8.4)	95.2 (8.9)	0.6 (0.8)	109.3 (6.5)	108.4 (6.4)	1.8 (1.6)	122.5 (7.1)	122.2 (6.6)	1.1 (0.7)
gait velocity [m/s]	1.10 (0.14)	1.09 (0.14)	0.01 (0.01)	1.39 (0.18)	1.37 (0.15)	0.04 (0.04)	1.73 (0.18)	1.79 (0.19)	0.06 (0.05)
foot angle [°]	28.3 (2.3)	26.9 (2.4)	2.0 (1.2)	30.9 (4.7)	28.9 (3.2)	2.9 (1.5)	36.3 (4.0)	34.0 (3.7)	2.8 (1.7)

Table 2: Gait parameters (means, SD in brackets) measured with GaitUp (GU) and Vicon (VI) in induced limping condition with slow (s), neutral (n) and fast (f) walking speed and absolute differences between the systems (ab-diff, mean), right leg, n=9

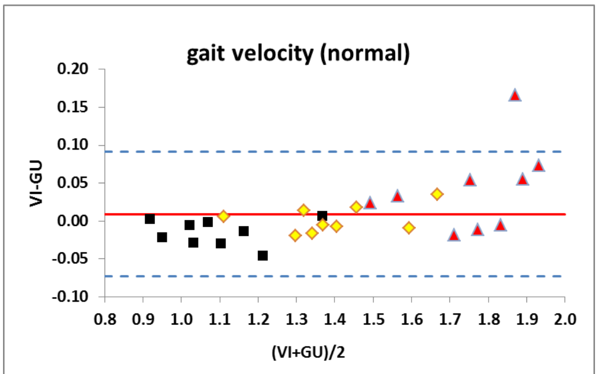
parameter (limping)	*GU-s*	*VI-s*	*ab-diff*	*GU-n*	*VI-n*	*ab-diff*	*GU-f*	*VI-f*	*ab-diff*
gait cycle time [s]	1.249 (.106)	1.253 (.105)	0.009 (0.005)	1.132 (.100)	1.138 (.087)	0.011 (.018)	1.019 (.062)	1.018 (.062)	0.005 (.006)
stride length [m]	1.438 (.113)	1.433 (.104)	0.021 (.015)	1.536 (.108)	1.548 (.129)	0.026 (.035)	1.718 (.106)	1.725 (.100)	0.040 (.038)
stride frequency [min^{-1}]	96.7 (8.8)	96.4 (8.8)	0.7 (0.3)	106.8 (10.1)	106.0 (8.3)	1.2 (2.3)	118.1 (7.6)	118.3 (7.6)	0.6 (0.7)
gait velocity [m/s]	1.15 (0.11)	1.15 (0.12)	0.03 (0.02)	1.37 (0.15)	1.37 (0.17)	0.03 (0.03)	1.68 (0.12)	1.70 (0.16)	0.05 (0.05)
foot angle [°]	26.9 (6.6)	30.8 (2.7)	5.7 (5.8)	28.8 (5.1)	28.3 (7.1)	5.9 (5.8)	32.8 (4.6)	26.6 (3.6)	8.3 (4.2)

Table 3: Correlations between the gait parameters measured with GaitUp and Vicon in normal and induced limping condition with slow, neutral and fast walking speed; n=9

	normal			*limping*		
parameter	*slow*	*neutral*	*fast*	*slow*	*neutral*	*fast*
gait cycle time [s]	0.995	0.919	0.985	0.996	0.986	0.992
stride length [m]	0.991	0.987	0.975	0.974	0.951	0.851
stride frequency [min^{-1}]	0.997	0.936	0.984	0.997	0.981	0.993
gait velocity [m/s]	0.994	0.970	0.968	0.957	0.967	0.908
foot angle [°]	0.643	0.837	0.806	-0.029	0.056	-0.530

The coefficients indicating the correlation between the two systems for each parameter and each condition are presented in Table 3.

The comparison of the results between the two measurement systems have been visualised for all parameters using Blant-Altman plots. The respective results for the gait velocity in the normal and induced limping condition are presented in Figure 1.



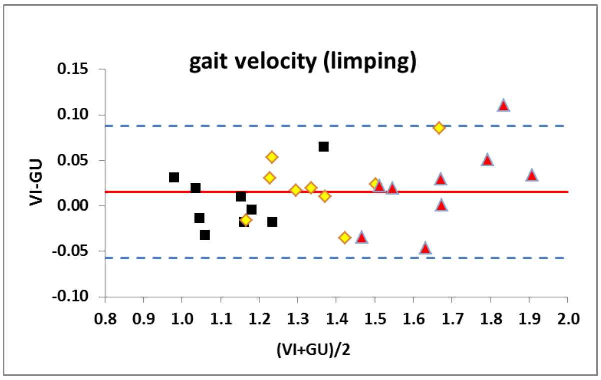


Figure 1: Bland-Altman plots comparing the gait velocity measured with GaitUp and Vicon in normal (left) and induced limping condition (right) with slow (squares), neutral (diamonds) and fast (triangle) walking speed

DISCUSSION: From a group perspective the two systems yield highly similar results with relative deviations less than 1% for the slow and neutral walking conditions in the normal walking setting. In the fast walking condition the differences partly exceed 3% (Table 1). For most of the parameters the relative deviations and the absolute differences between the two systems increase with walking speed. Relatively high deviations in all conditions have been observed for the foot angle at heel strike. Except for the foot planting angle all correlation coefficients for the remaining parameters exceed 0.92, in most conditions they are not lower than 0.97. The Bland-Altman plot for the gait velocity also indicates a high correspondence of the two respective data sets with a tendency of an overestimation by GaitUp at low speed and underestimation at high speed walking.
The general outcome of the comparative analysis regarding the gait parameters between the two measurement systems is closely in line with previously presented data for classical gait analysis in a clinical or therapeutic setting for not impaired participants (Mariani et al. 2010, Mariani et al. 2012, Brégou Bourgeois et al. 2013, Mariani et al. 2013). The deviations of the GaitUp in this setting from the 'gold standard' motion capture system are fairly small and stay within reasonable margins to guarantee valid and reliable data collection. The benefit of the easy and low cost usage of an IMU system exceeds by far the disadvantage of slightly diminished data accuracy.
To the best of our knowledge no data have been presented so far regarding the comparison of gait parameters collected using IMU systems with those from standard motion capture devices in a setting mimicking gait impairment (limping) by elevating the sole of one shoe. With exception of the parameter 'foot angle at heel strike' the comparative results with respect to absolute differences, relative deviations and correlations are very similar to those observed in the 'normal' gait conditions. This indicates that the IMU based measurement systems yield valid and reliable gait parameters also in limping patients. Large and not satisfying results have been gathered for the foot-angle on the elevated limb. The absolute differences between the GaitUp and the motion capture data range between 6° and 8° and the correlations are close to 0 or even negative for the fast walking condition. This variable obviously cannot be detected by the system are the algorithm with sufficient accuracy.

CONCLUSION: The IMU-based measuring system GaitUp (Physiolog4) yields fairly valid and reliable results in normal and limping walking conditions in a range of walking speed between 0.9 and 2.0 m/s. The absolute and relative errors show a tendency to reduced accuracy with increased walking speed. The advantage of IMU based measuring systems regarding simple handling and low cost usage justifies the application of this device in clinical, therapeutic and scientific settings despite the reduced data accuracy. For specific applications (e.g. impaired patients, inclined surface conditions) and the determination of particular variables additional adjustments or the development of appropriate software packages have to be considered to guarantee sufficiently high data quality with respect to accuracy, reliability and validity.

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