DEVELOPMENT OF A PROTOTYPE SMART APPAREL TO QUANTIFY RUNNING GAIT IN THE DAILY TRAINING ENVIRONMENT

Christopher J. Chapman[1], Devon H. Frayne[2], Vahid Babakeshizadeh[1]

Research and Development, PUSH Design Solutions Inc., Toronto, Canada[1]
Human Health and Nutritional Sciences, University of Guelph, Guelph, Canada[2]

Running gait kinetics and kinematics can be measured in the lab using force-instrumented treadmills and 3D motion capture. However, these tools are not feasible for use in the daily training environment of recreational and elite runners and track athletes. An inertial sensor-based prototype wearable smart garment (SG) has been developed to solve this problem. The purpose of this study was an initial assessment of SG compared to a force treadmill (FT) where foot-ground kinetics and temporal measures relevant to running were examined. Vertical ground reaction force, step time, and contact time showed "good to excellent" mean absolute percent error (< 6%), while step impulse did not (> 10%). All variables showed strong correlations between SG and FT (r > 0.85). The prototype smart garment is a viable option for the measurement of running biomechanics outside of the lab.

KEYWORDS: running, gait, IMU.

INTRODUCTION: In the lab, running gait biomechanics are measured with high validity and resulting efficacy using force treadmills and 3D motion capture. However, quantifying running biomechanics outside of the lab and in real world training environments remains a significant challenge. Numerous consumer-ready options exist including optoelectric grids, footwear insoles, video and inertial motion unit (IMU) systems (Fusca, 2018). However, these are often limited by cost and technical user requirements, do not meet the needs of the coach or support staff, and may disrupt the daily training environment. To address these gaps, PUSH has developed an IMU-based prototype wearable smart garment (SG) capable of collecting kinetic and kinematic data outside of the traditional laboratory setting, in a ubiquitous form factor that does not disrupt the coach-athlete training environment. The purpose of this study was to conduct an initial validation of the SG for use by both recreational runners and elite track and field athletes to determine if SG is a feasible option to collect gait biomechanics, and if further development is warranted based on these results.

METHODS: 3 participants (age = 26 ± 3.5yrs, height = 178 ± 7.4m, weight = 86.7 ± 15.5kg) who are recreational runners (run > 2x per week) completed two 3-minute walking trials (3, 4 km/h) and four 1-minute running trials (6, 8, 10, 12 km/h) on a force-instrumented treadmill (FT; DSI, Treadmetrix, USA). Participants donned the SG which is similar to compression pants worn in a standard off-the-shelf fashion. There are 5 IMU's embedded within the garment (Figure 1): one on each shank segment (anteromedial aspect), one on each thigh segment (lateral aspect), and one on the pelvis segment (posterior sacral aspect). After donning the SG, each participant completed ten minutes of walking/jogging to familiarize themselves with the FT followed by five minutes of self-selected warm-up consisting of dynamic and static stretching. After sufficient familiarization and warm-up, 52 retro-reflective markers were placed bilaterally on the lower limbs, pelvis and trunk of the participant on top of the SG (Figure 1). Positional data of these markers were collected throughout the movement trials. Prior to the movement trials, participants performed a stationary static calibration trial to relate the positions of the markers to specific limb segments and to the force transducers of the FT (Robertson, 2004). Additionally, dynamic knee flexion, hip flexion, and hip abduction trials were performed to orient the sensors within the SG to the respective joint motions of the participant.

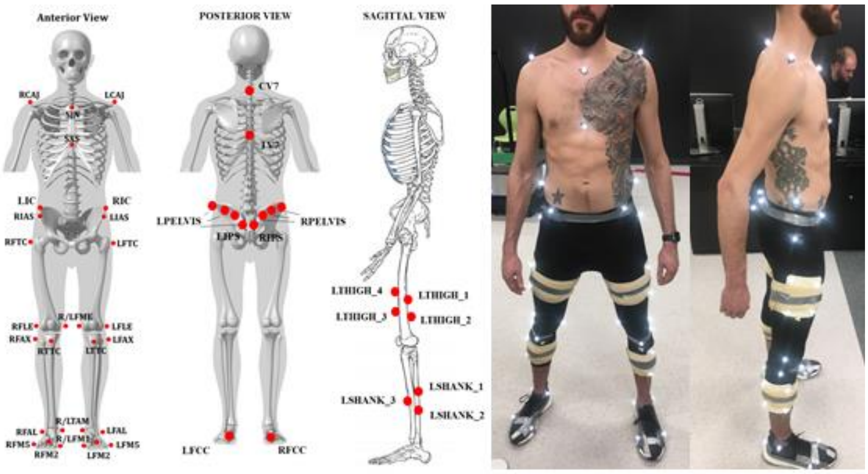

Figure 1: Marketset for kinematic data collection on force treadmill.

Three dimensional bilateral lower-limb, pelvis, and trunk kinematics (100 Hz, Qualisys AB, SWE), and foot-ground kinetics (1000 Hz, Treadmetrix, USA) were collected simultaneously in Qualisys Track Manager (QTM) and synchronized to the SG IMU data (100 Hz, PUSH, Canada). Raw QTM data were inputted into biomechanical modelling software (Visual 3D, C-Motion, USA) for processing. A seven-segment (pelvis, trunk, and bilateral foot, shank, and thigh) rigid-body linked-segment model was created from standing calibration trials for each participant. Marker position data and FT force data were low pass, bi-directionally filtered using a 4th order Butterworth filter with cut-off frequencies of 6 Hz and 20 Hz respectively. The filtered kinematic data were then used as inputs to the linked-segment model to compute the positions and orientations of the segments during the movement trials. An X, Y, Z Cardan rotation sequence was used to define the rotational motion of the modelled segments. The filtered kinetic data were used to define foot-strike and toe-off events as times when the vertical force on the treadmill exceeded and decreased a force threshold of 20 N, respectively. Step Contact Time is defined as the period spanning foot-strike to ipsilateral toe-off. Step Time is the period spanning foot-strike to contralateral foot-strike. Peak vertical ground reaction force (VGRF) and net vertical step impulse (time-integral of VGRF) were also calculated bilaterally during foot contact. SG data were processed using proprietary custom scripts (R version 3.3.2).

Left and right limb data were combined, and the mean and standard deviation across all participants and trials were reported. Mean absolute error and mean absolute percent error were also reported and computed as the difference between corresponding parameters assuming the FT as the true reference. Error classification was based on previously published criteria for the assessment of IMU data compared to criterion gait analysis (Fusca, 2018): excellent ($\%\varepsilon < 5$), good ($5 < \%\varepsilon < 10$), and sufficient ($10 < \%\varepsilon < 20$) and unacceptable ($\%\varepsilon > 20$). This criteria is based on four categories defined by standard statistical thresholds for significance analysis of clinical intervention (Jakobsen et al., 2014). Additional statistical analysis for assessment of SG includes Pearson product-moment correlation and standard error of measurement (SEM). SEM was derived using previous described methods (Batterham & George, 2000).

RESULTS: A total of 4076 steps were collected during the running trials. SG/FT data and error measures are provided in Table 1 and Table 2 respectively. Strong correlations between SG and FT were found for all variables ($r > 0.85$). Accuracy of the temporal measures of step time and contact time for SG were classified as "excellent". Kinetic measures showed larger amounts of error resulting in peak vertical ground reaction force and step impulse being classified as "good" and "sufficient" respectively.

Table 1: Comparison of running gait measure between PUSH Smart Garment (SG) and a Force-Instrumented Treadmill (FT). Data are presented as mean (± standard deviation).

	SG	FT	Absolute Error	Correlation (r)
Peak VGRF (N)	1705 (±518)	1626 (±463)	106 (±123)	0.96
Step Contact Time(s)	0.275 (±0.026)	0.270 (±0.033)	0.014 (±0.012)	0.87
Step Time (s)	0.366 (±0.02)	0.367 (±0.02)	0.007 (±0.007)	0.86
Step Impulse (N•s)	280 (±69.3)	261 (±71.4)	24.9 (±17.7)	0.94

Table 2: Error measures for PUSH Smart Garment (SG) versus the criterion measures (FT). Standard error of measurement (SEM); mean absolute percent error (%ε).

	SEM	%ε	Error Classification (Fusca et al. 2018)
Peak VGRF (N)	98.3	5.8	Good
Step Contact Time(s)	0.009	4.6	Excellent
Step Time (s)	0.006	1.9	Excellent
Step Impulse (N•s)	16.5	10.0	Sufficient

DISCUSSION: According to the criteria proposed by Fusca and colleagues (2018) for the validation of IMU-based technology for gait biomechanics, when compared to criterion lab methodologies the initial prototype SG can measure the temporal and kinetic measures of running gait. Fusca specifically created this criterion for the validation of IMU-based gait analysis versus lab standard techniques, primarily due to the widespread accessibility and rapid advancements in IMU technology. Overall, temporal measures had less relative error compared to FT (%ε < 5%), but displayed greater disparity in the trendline (r = 0.86-0.87). Conversely, the kinetic measures displayed higher error (%ε > 6%) with higher correlations (r >0.94), indicating greater similarity in the trendlines of SG and FT.

Data garnered from the SG has the potential to assist in the mitigation of training related injuries and the improvement of athlete performance. The etiology of running-related injuries is multifactorial, implying that many interacting biomechanical measures present as risk factors for sustaining an injury (Bertelsen et al., 2017). Accordingly, it is prudent for professionals in this domain to be able to continuously measure a constellation of biomechanical variables during multiple running sessions over time to stand the best chance of capturing risky running behavior for an individual. The SG provides a method for capturing this type of data not bound by the environmental restrictions associated with laboratory environments.

As with risk factors concerning running-related injuries, diverse kinetic and kinematic parameters have been implicated in limiting running performance (Moore, 2016). Unlike in the laboratory, where unique data collection systems often have to be synchronized to simultaneously collect kinetics and kinematics, the SG offers a single piece of equipment designed to garner both types of data from runners in the real-world.

This validation study is relevant for running athletes (i.e., recreational runners, track and field competitors), their coaches, and support staff (i.e., sport scientists, biomechanists) as the wearable garment form factor allows for the transformation of the daily training environment into a testing environment allowing gait biomechanics to be measured and monitored ubiquitously without disruption. Furthermore, the SG reports bilateral information on athletes' gait cycles which provides the opportunity to assess progression of asymmetries across a long training session. Future prototype development will involve the assessment of kinematic measures such as lower limb joint angles, vertical and horizontal whole-body center-of-mass displacement and injury-related measures such as tibial acceleration (Milner et al., 2006).

CONCLUSION: The overall positive findings would indicate the prototype wearable smart garment (SG) developed by PUSH is a viable option to collect running biomechanical data outside of the lab in the daily training environment. Further prototype development is warranted in an attempt to bring SG even closer to criterion lab-based measurements by bringing all observed measures within "excellent" accuracy error thresholds.

REFERENCES

Batterham, A. & George, K. (2000) Reliability in evidence-based clinical practice: A primer for allied health professionals. *Phys. Ther. Sport*. 1:54–61

Bertelsen, M.L., Hulme, A., Petersen, J., Brund, R.K., Sorensen, H., Finch, C.F., Parner, E.T. & Nielsen R.O. (2017). A framework for the etiology of running-related injuries. *Scandinavian Journal of Medicine & Science in Sport.* 27(11):1170-80.

Fusca, M., Negrini, F., Perego, P., Magoni, L., Molteni, F. & Andreoni, G. (2018). Validation of a wearable IMU system for gait analysis: Protocol and application to a new system. *Applied Sciences.* 8:1167-82.

Jakobsen, J.C., Gluud, C., Winkel, P., Lange, T. & Wetterslev, J. (2014) The thresholds for statistical and clinical significance - A five-step procedure for evaluation of intervention effects in randomised clinical trials. *BMC Med. Res. Methodol.* 14:34.

Milner, C.E., Ferber, R., Pollard, C.D., Hamill, J. & Davis, I.S. (2006) Biomechanical factors associated with tibial stress fracture in female runners. *Medicine & Science in Sports & Exercise.* 38(2):323-8.

Moore, I.S. (2016). Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy. *Sports Medicine.* 46(6): 793-807.

Robertson, D.G.E., Caldwell, G.E., Hamill, J., Kamen, G. & Whittlesey, S.N. (2004). Research Methods in Biomechanics. Winsor: Human Kinetics.

ACKNOWLEDGEMENTS: This research is part of a joint project between PUSH and Athletics Canada funded by the Built in Canada Innovation Program (BCIP). Data collection was completed at the Humber College Institute of Technology as part of an industrial partnership with PUSH.