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a preliminary analysis

Chatterton, Gustav J.; Bang Hansen, Jesper; Hoelgaard Kristiansen, Nikolaj; Kunwald, Nikolaj Pelle; Kersting, Uwe Gustav; Oliveira, Anderson Souza

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ASSESSING KINEMATICS AND KINETICS OF HIGH-SPEED RUNNING USING INERTIAL MOTION CAPTURE: A PRELIMINARY ANALYSIS

Gustav J. Chatterton[1], Jesper B. Hansen[1], Nikolaj H. Kristiansen[1], Nikolaj P. Kunwald[1], Uwe G. Kersting[1,2] and Anderson S. Oliveira[3]

Department of Health and Technology, Aalborg University, Denmark[1]
Department of Biomechanics, German Sport University Cologne, Germany[2]
Department of Materials and Production, Aalborg University, Denmark[3]

The purpose of this study was to determine whether inertial motion capture (IMC) in combination with musculoskeletal modeling is a suitable method to assess lower limb kinematics and kinetics during high-speed running. Optical motion capture (OMC), IMC and ground reaction forces (GRF) were used as input for musculoskeletal models. Kinematics showed excellent correlations (knee: ρ=0.98, rRMSE=21.0%, hip: ρ=0.95, rRMSE=18.5 %, ankle: ρ=0.93, rRMSE=46.6%). The ground reaction force predictions showed varying results (anteroposterior: ρ=0.77, rRMSE=33.4%, mediolateral: ρ=0.04, rRMSE=69.1%, vertical: ρ=0.78, rRMSE=25.7%). The examined IMC and musculoskeletal modeling approach was proven a useful alternative to OMC and force plates for outdoor measurements in high-speed running.

KEYWORDS: Sprinting, Ground reaction force prediction, Inverse dynamics, Musculoskeletal modeling.

INTRODUCTION: Hamstring injuries are the predominant injury in numerous of sports requiring high speed running (Dalton et al., 2015; Ekstrand, 2013). It is well established that hamstring injuries often occur during high-speed running (Elliott et al., 2011; Woods, 2004), and assessing biomechanical properties from high-speed running may provide relevant information regarding the hamstring's injury mechanisms. The state-of-the-art in movement analysis is optical motion capture (OMC) combined with force plates that provide GRF. These combined methods allow the estimation of muscle forces, lengths and muscle recruitment using inverse dynamics (Damsgaard et al., 2006). However, OMC is predominantly applied in laboratory settings, limiting the assessment of the athlete's behavior in natural conditions (e.g., during football maneuvers). An alternative method to overcome this limitation may be performing motion capture using inertial measurement units (IMUs), which allows accessing three-dimensional motion capture in-field testing (Zhang et al., 2013). Moreover, the use of kinematic outputs from inertial motion capture (IMC) in combination with musculoskeletal modelling is a suitable method to predict GRF from walking and lifting activities (Karatsidis et al., 2018; Larsen et al., 2020). However, it is yet to be shown whether IMC is a suitable method to the extraction of kinematics and kinetic parameters during high-speed running. Therefore, the aim of this study was to determine the accuracy of kinematics and kinetics parameters extracted from IMC during high-speed running when compared to OMC.

METHODS: Participants: Fourteen young males with no history of hamstring injuries and no present musculoskeletal or neuromuscular disorders were recruited for the study (age: 24.9 ± 3.1, height: 185.6 ± 4.7, weight: 83.5 ± 7.4, body mass index (BMI): 24.3 ± 2.4) complying with the institutional ethical board regulations.

Experimental protocol: Measurements from IMC and OMC were synchronized using the Xsens Awinda sync station (Xsens Technologies BV, Enschede, Netherlands). The OMC system captured trajectories of 40 reflective markers. The marker trajectories were captured by 18 high speed infrared cameras (Oqus 700+, Qualisys, Göteborg, Sweden), while the IMC system recorded data from 17 IMUs (Xsens MVN Link Technologies BV, Enschede, Netherlands). The sampling rate of both systems was 240 Hz. The GRFs were measured using a floor mounted force plate (Bertec Corp, Columbus, OH) sampled at 1200 Hz. The test protocol consisted of four maximal sprints on a 30-meter track in the laboratory. A five-minute rest period was allowed between sprints, to minimize the influence of fatigue. Subjects were tested until four successful trials were recorded or fatigue occurred.

Musculoskeletal models and scaling: Two musculoskeletal models were constructed using a dedicated modeling software (AnyBody Modeling System v. 7.3, AnyBody Technology A/S, Aalborg, Denmark): a model derived from OMC and measured GRF (OMC-MGRF) and a model derived from IMC and predicted GRF (IMC-PGRF). The GRF were predicted by the AnyBody software, using a modified method of Karatsidis et al. (2018). For each subject, the OMC data for the specific trials were used to scale the models, using a least-squares minimization method between the model and the input derived from the reflective marker positions (Andersen et al., 2010). The IMC models' segment lengths were derived directly from the stick figure generated in Xsens MVN studio using measured body dimensions.

Data analysis: The force measurements, optical and inertial marker trajectories were low-pass filtered (2nd order, 15 Hz Butterworth). The following variables from OMC-MGRF and IMC-PGRF were extracted; knee and hip joint flexion/extension angles, ankle plantar/dorsiflexion angles, vertical, anteroposterior and mediolateral GRFs. Pearson's correlation coefficients (ρ) and relative root-mean-square error (rRMSE) were calculated on a subject basis between the IMC and OMC time series of the hip, knee and ankle kinematics and predicted GRF. One-dimensional statistical parametric mapping (SPM) paired t-test were used for comparison between OMC-MGRF and IMC-PGRF variables. The significance level was set at $p<0.05$.

RESULTS: The average sprinting speed was 7.66± 0.37 m/s. There were strong to excellent correlations between IMC and OMC measurements (Table 1), except the mediolateral component for the GRF prediction. The rRMSE ranged from 18.5 to 69.1%, while the rRMSE inter-subject fluctuated between 13.8% to 93.9% across all variables.

Table 1: Pearson's correlation (*ρ*) with standard deviation, rRMSE and their respective ranges.

	ρ	Range	rRMSE	Range
Knee flexion/extension	0.98 ± 0.02	0.91 - 0.99	21.0 ± 4.30 %	13.8 - 31.5 %
Hip flexion/extension	0.95 ± 0.02	0.92 - 0.99	18.5 ± 5.42 %	10.0 - 33.2 %
Ankle plantar/dorsiflexion	0.93 ± 0.04	0.81 - 0.98	46.6 ± 11.8 %	27.8 -66.6 %
Anteroposterior GRF	0.77 ± 0.12	0.52 - 0.95	33.4 ± 8.11 %	21.3 - 51.9 %
Mediolateral GRF	0.04 ± 0.49	-0.79 - 0.59	69.1 ± 16.8 %	42.6 - 93.9 %
Vertical GRF	0.78 ± 0.16	0.38 - 0.94	25.7 ± 5.34 %	14.1 - 35.1 %

There was a significant difference between the models in the knee and ankle angles for the entire running cycle (Figures 1A, 1B, 1E and 1F), and for the majority of the running cycle for the hip flexion/extension (Figures 1C and 1D). Regarding GRF, there were no significant differences between the two models for the majority of the running cycle, except between from 0-6% and between 92-100% (Figure 2A and 2B) for anteroposterior GRF, from 6-20% for mediolateral GRF (Figure 2C and 2D) and from 0-4% for vertical GRF (Figure 2E and 2F).

DISCUSSION: The excellent correlations found for knee and hip flexion/extension and ankle plantar/dorsiflexion corroborates the results of Karatsidis et al. (2018). However, our relative errors were higher (knee: 7.2 ± 3.4%, hip: 12.7 ± 5.3%, ankle: 14.0 ± 4.8%). Karatsidis and co-workers validated the IMC during normal walking, while the present study investigated high-speed running that involves high impacts and segment/angular velocities, resulting in higher peak forces and velocities. Walking kinematics and kinetics are usually filtered with lower cut-off frequency when compared to high-speed running, smoothing data segments that may differ when using higher cut-off frequencies, ultimately minimizing relative errors. The IMC system generally showed a significantly more flexed knee and hip joint angle, and a more extended ankle joint angle. IMC calibration might influence the relative position of segments, explaining the consistent differences in joint angles. Moreover, different segment scaling between systems may influence the GRF prediction around toe-impact and toe-off. The scaling of the

IMC model was done by manual measurement of the segments and the scaling for the OMC was done by marker placement. Since knee flexion in IMC-PGRF was higher than for OMC-MGRF (i.e., more flexion; Figure 1A), it results in smaller strain of the hamstring muscles, which is undesirable when investigating hamstring injury risks (Schache et al., 2012; Thelen et al., 2005). On the other hand, overestimating the hip flexion results in higher hamstring muscle strain and is therefore also undesirable. Future studies investigating IMC models using segment scaling from OMC models are necessary to define whether the difference in joint angle is related to segment scaling.

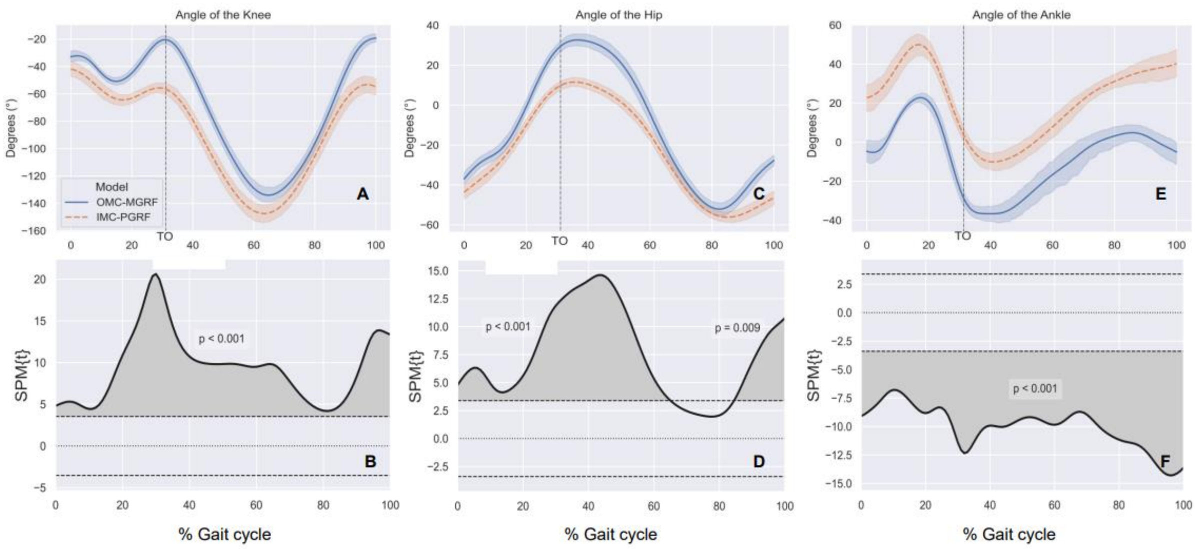

Figure 1: Mean and SPM from knee, hip and ankle kinematics for IMC-PGRF and OMC-MGRF.

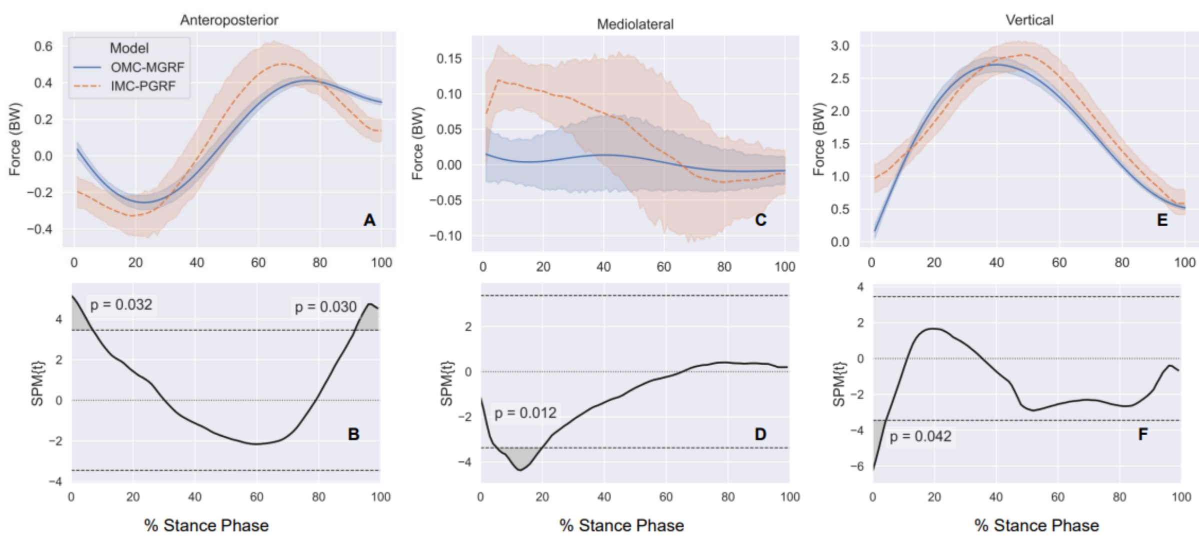

Figure 2: Mean and SPM plots presenting the GRF prediction for IMC-PGRF and the OMC-MGRF.

The strong correlations and moderate differences in relative magnitude for the anteroposterior and vertical GRF's are comparable to previous literature on comfortable running pace (Skals et al. 2017) (anteroposterior: ρ=0.88 ± 0.12, vertical: ρ=0.99 ± 0) and walking (Karatsidis et al. 2018) (anteroposterior: ρ=0.91 rRMSE=15.0 ± 2.5%, vertical: ρ=0.97 rRMSE=7.7 ± 2.1%). In general, lower correlations and higher rRMSE were found in our study compared to the literature (Karatsidis et al., 2018; Skals et al., 2017). However, investigating high-speed running biomechanics presents greater challenges for data acquisition when compared to other movement types. Nonetheless, the poor correlation and rRMSE for the mediolateral GRF described in our results was also reported during walking tasks (Karatsidis et al. 2018). These authors suggested that the poor results for the mediolateral direction are related to the low magnitude of the signal, which reduced the signal-to-noise ratio and exacerbates the computed errors. This assumption is supported by previous work (Skals et al., 2017) that investigated side-cutting maneuvers, which present greater mediolateral signal magnitudes. In this case, there were excellent correlations between OMC and the force plate (ρ = 0.96 ± 0.02). Therefore, it might not be possible to extract highly similar GRF from the mediolateral component when analyzing forward locomotion (walking/running).

CONCLUSION: Our results indicate high correlations between kinematics and kinetics parameters extracted from IMC and OMC, whereas the relative errors are higher than those presented in other studies investigating walking. Therefore, IMC may be a relevant method to assess kinematics and kinetics of high-speed running in natural conditions. However, further studies investigating the performance of an IMC based model at different running speeds and different moving directions are necessary to confirm our results.

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