2D JOINT KINEMATICS AND KINETICS ESTIMATE USING A SINGLE MAGNETIC AND INERTIAL MEASUREMENT UNIT DURING A SQUAT EXERCISE

Vincent Bonnet¹, Claudia Mazzà¹, Philippe Fraisse² and Aurelio Cappozzo¹
¹LABLAB, Department of Human Movement and Sports Sciences, University of Rome “Foro Italico”, Italy
²LIRMM UMR 5506 CNRS, Univ. Montpellier 2, France; email: bonnet.vincent@gmail.com

SUMMARY
We investigate dynamic optimization as a tool to estimate joint kinematics and kinetics, and ground reaction forces (GRFs) using data from a single magnetic and inertial measurement unit (MIMU) positioned on the lower trunk. The redundant squat-task mechanics was solved by minimizing a dynamical cost function under task constraints.

INTRODUCTION
Interest in MIMUs for human motion measurement has grown in recent years due, in part, to their ease of use [1]. Usually, IMUs are attached to adjacent body segments to estimate joint kinematics [1,2,3]. The challenge for clinical applications was computed using recursive Newton-Euler equations. The lengths and inertial parameters of the model. Inverse dynamics double differentiation of its coordinates.

METHODS
Biomechanical model
The biomechanical model of the human body was planar (sagittal plane) and composed of four rigid segments (feet, shanks, thighs, trunk) connected by cylindrical hinge joints (Fig. 1). De Leva tables [5] were used to estimate segment lengths and inertial parameters of the model. Inverse dynamics was computed using recursive Newton-Euler equations. The acceleration of the CoM of the model was obtained by a double differentiation of its coordinates.

Optimization process
The redundant squat task mechanics was formulated as a mathematical optimization problem with an objective function based on the minimization of a dynamical cost function. Kuzelicki et al. [6] proposed a criterion, specific for mechanical demanding postural tasks, that is the combination of the sum of the intersegmental couples and of their derivatives:

\[ J_r = \sum_{i=1}^{n} \left( J_{TF} \right) \left( t_i \right) + J_{GRF} + J_{UP} \]

where \( n \) is the number of discrete time instants \( t_i \) and \( \Delta t \) is the sampling interval.

In the optimization search, joint positions \( \theta_i \) have been described trough Fourier series:

\[ \theta_{r,i}(t) = a_{k_0} \cos(k_0 t) + b_{k_0} \cos(k_0 t) \]

where \( a_{k_0} \) and \( b_{k_0} \) are the amplitude coefficients for the \( k_0 \) harmonic of the \( k_0 \) joint, \( \omega = 2\pi T_F \) is the pulsation of the motion. The number of harmonics in the Fourier series was set to \( N=8 \).

Equality constraints (tolerance 5%) based on head position were used to drive the biomechanical model while performing the squat task:

\[ Y_{head} \left( \frac{T_F}{2} \right) = Y_{head}(1) - Y_{wd} \]

\[ \theta(t) = \theta_{up} \]

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where \( T_F \) is the task execution time and \( \theta_{up} \) was set to [\( \pi/2; 0.0 \)]. A second constraint was associated with dynamical balance maintenance:

\[ CoP_{min} \leq CoP(t) \leq CoP_{max} \]

where \( CoP_{min} \) and \( CoP_{max} \) are defined by the subject foot length.

The measured acceleration component \( \dot{A}_y \) was used as a constraint for the vertical acceleration of the model CoM (\( \ddot{CoM}_{y} \)):

\[ A_y(t) - \varepsilon \leq \ddot{CoM}_y(t) \leq A_y(t) - \varepsilon \]

where \( \varepsilon = 0.25 \text{m/s}^2 \) is a chosen tolerance error value.

The optimization problem consisted in minimizing \( J_r \) by finding the \( 2(2N+1) \) coefficients of the Fourier series, representing \( \theta_1 \) and \( \theta_2 \), that make the model move respecting the above constraints and the measured trunk inclination.

Experiment
Two subjects (1 male, mass=70kg, stature=1.75m; 1 female, mass=60kg, stature=1.70m) were asked to perform a squatting
task starting from the upright position (UP), lowering the head by $Y_{tor}=0.2m$, and then return to UP. Participants were asked to keep their arms folded across the chest and the soles flat on the ground. The task was repeated 15 times with rest between the trials. A force plate (Bertec) was used to record the GRFs and a MIMU (MTx, Xsens Motion Technologies) was attached to the lower trunk (Fig. 1) to record trunk inclination $\theta_t$ in the sagittal plane and the linear acceleration vector local components. Kinematic variables were simultaneously measured using a stereophotogrammetric system ($9 Mx$ cameras, VICON) as associated with the Davis protocol [7]. The hip angle $\theta_h$ was computed as the summation of $\theta_t$ and $\theta_2$ and of $\theta_T$ (Fig. 1).

Model validation
To validate the model, its outputs were compared to the measured joint angles and vertical component of the GRF and the normalized root mean square difference (NRMSE), the proportion of variance accounted for ($R^2$) and the correlation coefficient ($r$) were calculated.

RESULTS AND DISCUSSION

![Figure 2: Typical results obtained for subject 1 (top) and subject 2 (down). (a) Joint angles. (b) Vertical GRF.](image)

The features of the GRFs were markedly different between the two subjects (Fig.2). Nevertheless, the model was able to reproduce the vertical GRF with a maximum NRMSE difference of 3.1%. For all joints and all trials, the NRMSE difference in the joint angles was less than 12.5%, with the highest difference exhibited by the knee mostly due to an offset between the curves (Table 1). The $r$ values show that the timing of the task execution is respected with a lowest correlation at 0.97. Finally, the $R^2$ showed the good fit with the data points obtained through stereophotogrammetry.

CONCLUSIONS
Preliminary results obtained with the proposed methodology were very encouraging. The use of a dynamical cost function and the task constraints imposed in the optimization process allowed for a reliable estimate of joint kinematics and vertical GRF. It has to be noticed that this approach is based on hypotheses that are likely to be more related to motor control strategies [6] than most commonly used techniques base on the minimization of the difference between estimated and measured variables [8]. Further work will focus on not using the magnetometer for the reconstruction of trunk inclination and on the validation using a larger number of subjects.

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REFERENCES

| Table 1: Summary of model validation results. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | NRMS Ankle (%)  | NRMS Knee (%)   | NRMS Hip (%)    | NRMS GRF (%)    | $R^2$ Ankle (%) | $R^2$ Knee (%)  | $R^2$ Hip (%)   | $R^2$ GRF (%)   | r Ankle (%)     | r Knee (%)      | r Hip (%)       | r GRF (%)       |
| Subject 01     | 5.6 ± 1.6       | 8.9 ± 4.2       | 6.4 ± 2.0       | 2.9             | 99.8 ± 1.1     | 105.0 ± 8.7     | 95.9 ± 3.3      | 91.0 ± 34       | 0.99           | 0.99           | 0.99           | 0.99           |
| Subject 02     | 6.4 ± 3.0       | 12.4 ± 3.5      | 10.6 ± 2.0      | 3.1             | 96.2 ± 14.0    | 112.1 ± 5.6     | 95.1 ± 7.7      | 99.7 ± 11.0     | 0.97           | 0.97           | 0.97           | 0.97           |