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# Application of a Functional Method for Subject and Motion Specific Joints Kinematics during Walking

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## Abstract

Quantitative, as well objective human motion analysis has a prominent role in many research fields of biomechanics, such as for gait analysis purposes. Focusing on joints kinematics, several aspects like the kind of movement, the measurements, the post-processing techniques and the adopted human multi body model within the joints approximation have to be taken into account to ensure a consistency of outcomes both in terms of reliability and repeatability.

In particular, both kinematic and dynamic calculations require an accurate method of joints parameters estimation, like centers and axes of rotation, resulting in a different definition of joints coordinates systems and of motion patterns computation, as a consequence.

Predictive and functional methods can be used to estimate joints parameters. Considering some drawbacks like the restrictive protocol for markers positioning on precise anatomical landmarks and the following lack of accuracy, which are typical of the former approach, the aim of this study is to evaluate the feasibility of a functional method to simultaneously estimate lower limbs joints parameters during walking.

Markers-based stereo-photogrammetric motion capture sessions are performed in order to acquire data to be used as input of a functional algorithm. A validation of this latter is provided with a subject-specific multi-body model, implemented in OpenSim, properly scaled by means of the estimated joint centers. Moreover, gait kinematics curves are computed by solving an inverse kinematics problem exploiting a global optimization method.

A final comparison with the gold standard technique is provided in terms of root mean squared errors and cross-correlation coefficients to evaluate the outcomes consistency for the presented pilot study.

**Keywords:** Biomechanics; Gait; Joints; Functional methods; Global Optimization Method, OpenSim.

## INTRODUCTION

Human biomechanical models based on multi-body dynamics are used to study the biomechanics of human movement, in order to quantify motion and to compute joint kinematics, as well dynamics. Human motion analysis is traditionally applied to gait analysis and enclosed in clinical laboratory, but nowadays there is a strong interest to apply it also to many other different fields (sports, ergonomics, military applications, movie industries, manufacturing industries, etc).

In general human motion involves the coordination and the interaction of the muscoloscheletal system and of the nervous system. In this scenario an accurate definition of body segments coordinates systems is required due to the emphasis set on the relative motion between body segments, hence on joint angles. Thus, joints parameters estimation like axes or centers of rotation (AoRs and CoRs) is a crucial issue, considering how these ones highly influence human motion patterns. As a consequence, articular joint model within its parameters is important to assess what is not directly measurable in vivo [1, 2]. Moreover, an accurate estimation of joints parameters becomes necessary especially for people affecting by pathologies or presenting physical deformities directly compromising motion tasks, as well kinematics [3].

Joint parameters can be estimated according to different approaches [4, 5]: predictive and functional methods. The laboratories of human motion analysis actually adopt predictive methods (PMs), based on regression equations [6]. This approach requires specific protocols for markers positioning on anatomical landmarks, resulting in a main drawback, due to the not often easily identification. Despite the easy-of-use, this method may lack of accuracy, resulting in several errors [2, 5], particularly with nonstandard cases. Thus, functional methods (FMs) are proposed to remedy problems and limits affecting joints parameters estimation with the former approach. They do not refer to empirical relations and are just based on the relative motion between two body segments with respect to the considered joint. To this end, customized markers-based protocols are considered in order to define the relative segments position and orientation, not requiring the palpation of anatomical landmarks and by using 3-markers set at least on each body segment. Several strategies are proposed in literature, providing a 2-categories classification of FMs in fitting approaches and coordinates transformation techniques. The former are variants of the sphere-fitting method [7], where each marker can rotate around the same joint axis or center of rotation with a separate arc [8, 9], without a body rigid assumption. The second considers instead each body segment as a rigid one to enable the definition of a local coordinate system and rigid transformations into a global reference frame [10, 11]. Functional methods are nevertheless based on several combinations of kinematical and geometrical constraints, as well optimization techniques, providing good results in certain conditions [12, 13], e.g. with a proper range

of motion (RoM). Several studies reported in literature [7, 12] underline that FMs provide more accurate results respect to the PMs, although both are influenced from the soft tissue artifacts (STAs) [5]. Once three FMs [8, 11, 13] have been discussed, implemented and tested, in a previous study [14, 15], on a knee mechanical analog with a dummy of the lower limb, authors focus on a follow-up work.
This research aims to evaluate the feasibility of gait kinematics trends computation using a FM [12] for joints parameters estimation and a subject-specific human modeling technique. A first attempt to validate the proposed approach is analyzed and discussed, comparing the obtained gait trends with the gold standard ones.

## MATERIALS AND METHODS

Understanding the real joint kinematics is important to comprehend how the considered joint may be modelled. The complexity of a biomechanical model is related to the large variety of joint types and body shapes and is ascertained that many assumptions have to be taken into account to model the human body as a multibody system. As a consequence, joint kinematics depends on many aspects including also the adopted human body model within the articular joints approximation. The position and the orientation of body segments, as well joints parameters computation, derive from Motion Capture (MoCap) data provided in this study with a stereo-photogrammetric markers-based technique. The methodology here considered can be summarized as in Fig.1, and later detailed.

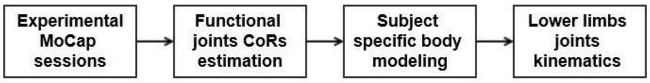

**Figure 1:** Sketch of the methodology

### *Experimental MoCap sessions*

A stereo-photogrammetric MoCapVicon® 460 system (Oxford Metrics, Oxford, UK), based on a set of 6 cameras working at 100 Hz was used. One healthy subject (male, 28 years) was asked to walk at his self-selected walking speed performing 10 gait trials of some steps. A specific markers-based Helen Hayes protocol was considered by positioning markers (diameter 14 mm) on anatomical landmarks for the PM-based approach. Anthropometric measurements, like the leg length, the knee width and the ankle width were collected in order to estimate the lower limbs kinematics according to the standard procedure [5, 16]. Moreover 3-markers sets (Fig. 2A) were placed on each lower body segments to be used as input for the chosen functional algorithm [12, 13]. As aforementioned in the previous section these functional markers were placed without anatomical landmarks constraints.

### *Functional joints CoRs estimation: subject specific body modeling*

The trajectories of each marker provided by the Vicon post-processing were used as input for the FM *SCoRe* (*Symmetrical Center of Rotation estimation*) [12]. According to this algorithm, local reference frames can be defined for each couple of adjacent body segments, connected by the considered joint and in relative motion. Considering that the center of rotation with respect to body segment 1 ($c_1$) and to body segment 2 ($c_2$) is the same, is possible to introduce an objective function $f_{Score}$ that can be minimized with a linear least square method to evaluate $c_1$ and $c_2$. Given n as the number of the total acquired frames during motion, is possible to define both orientation matrices ($R_i$, $S_i$) and translation vectors ($t_i$, $d_i$) for each considered *i*-frame and each segment respectively. Thus, equation (1) can be derived:

$$f_{Score}(c_1, c_2) = \sum_{i=1}^{n} \left\| R_i \cdot c_1 + t_i - (S_i \cdot c_2 + d_i) \right\|^2 \qquad (1)$$

Once the hip, the knee and the ankle CoRs have been estimated with the FM previously detailed, a multibody model implemented with an open-source software OpenSim [15] has been considered, in order to validate and assess the goodness of the solutions obtained with the FM. In OpenSim the musculoskeletal model is defined by bodies (bones), joints (articulations), actuators (muscles) and key points (markers) that can be customized. This allows to compare, as in this case study, the resulting relative joints angles with respect to the standard ones, according to the orthopaedic angles [17]. Joints were modelled with appropriate DoFs, consistently defined according to the conditions imposed by the functional algorithm [12]. A subject-specific human model was implemented by means of a scaling process that allows to define a scale factor for each lower body single bone (Fig. 2A). To this end the functional joint CoRs previously estimated have been used, compared to those defined in the model, corresponding to the origins of local reference systems.

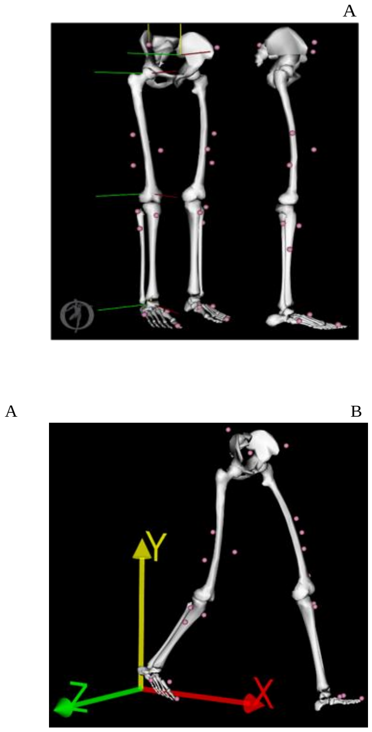

**Figure 2:** Multibody model (A), and walking trials after inverse kinematics (B).

### *Lower limbs joints kinematics*

Once MoCap acquisitions have been post-processed in order to obtain the three-dimensional experimental coordinates of each marker, an inverse kinematics problem is solved. Indeed the experimental data have been imposed into the model in order to simulate and replicate the acquired motion (Fig. 2B), exploiting the global optimization method [18]. Unknown joint angles have been extracted in order to minimize the squared error (SE) according to equation (2). Thus, for each *i*-marker is possible to compare the experimental position vector $p_i^E$ with the virtual one $p_i^V$of the model, with a proper set of weight $w_i$, defined inversely proportional to the amount of STA associated to each marker. The second part, related to the *j*-joint is instead considered if known initial joints constraints are available, always comparing the experimental configuration and the virtual one. Therefore, joints angles which best replicate the real configuration can be estimated:

$$SE = \mathbf{min}\left( \sum_{i=1}^{m} w_i \cdot \left\| p_i^E - p_i^V \right\|^2 + \sum_{j=1}^{j} w_j \cdot \left\| \theta_j^E - \theta_j^V \right\|^2 \right) \quad (2)$$

## RESULTS AND DISCUSSION

A comparison with respect to the gold standard kinematics curves has been carried out, in order to evaluate the feasibility of the FM-based approach with direct measurements performed during gait analysis sessions. Results obtained using the FM focus on 3D gait kinematics patterns for the lower limbs joints. Fig. 3 shows, for each joint of the right leg the resulting kinematics trends (blue lines) compared to the standard ones (red lines) and to the reference normal bands (black lines related to the mean values and the standard deviations). Root Mean Square Errors (RMSE) and correlation coefficients (CC) between the two techniques are summarized in Table 1, considering the mean values and the standard deviations, related to the results averaged on10 trials.

This study mainly aims to assess the feasibility of a FM [12] used to estimate lower limbs joints parameters, in order to compare gait trends with the standard ones, during gait analysis. The obtained results seem consistent for the declared purposes, as reported in Table 1. According to what is shown in Fig. 3 there is an higher variability for the coronal and the transversal planes, particularly for the knee joint. This may be due to the accuracy of the adopted joint model, but also to the markers residuals involving in the global optimization method, hence to the STA. Moreover, considering that the major RoM during walking occurs on the sagittal plane, RoMs related to the other planes are lower and maybe interfere with the FM ideal conditions [12, 13].

Model modifications, additional motion tasks, as well larger sample data will be considered in further studies in order to evaluate the reliability of the FMs instead of the current PMs, with also nonstandard cases. Also different motion capture acquisition system, e.g. by using wearable sensors [20, 24], which could be useful to propose a markerless-based functional approach for joints kinematics, will be examined.

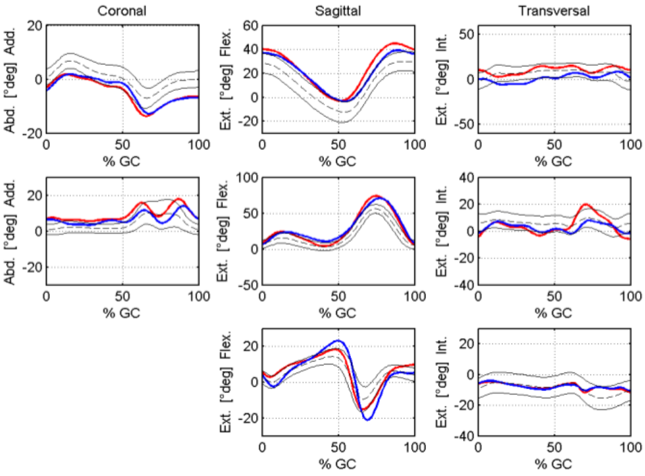

**Figure 3:** Gait kinematics curves using FM (blue) or PM (red) compared with normal bands (black). Graphs related to the hip (top), to the knee (middle) and to the ankle (bottom).

**Table 1:** RMSE and CC data analysis for each anatomical plane.

| Joint | Coronal | | Sagittal | | Transversal | |
|---|---|---|---|---|---|---|
| | RMSE [°deg] | CC | RMSE [°deg] | CC | RMSE [°deg] | CC |
| Hip | 1.35 ± 0.09 | 0.97 | 4.44 ± 0.25 | 0.98 | 7.13 ± 1.20 | 0.84 |
| Knee | 3.54 ± 1.56 | 0.86 | 4.27 ± 0.27 | 0.99 | 5.15 ± 0.28 | 0.71 |
| Ankle | -- | -- | 4.55 ± 0.29 | 0.93 | 1.00 ± 0.56 | 0.96 |

## CONCLUSION

The presented methodology allowed to overcome problems related to the PM-based computation, to reduce time and costs for the experimental setup, to compute both a subject-specific and motion specific analysis in order to accurately study motion patterns for further purposes. Test realized during gait trials performed by a pilot healthy subject, as well the obtained outcomes, encourage authors to continue to plan further measurements and evaluations of the proposed methodology.

Moreover, functional methods merge well with new techniques based on inertial sensors. This allows to foresee new field of motion analysis application, since they may be employed for different purposes and in many different environments [21-24], and not only in laboratory ones.

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