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Physiologically corrected coupled motion during gait analysis using a model-based approach

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ABSTRACT

Gait analysis is used in daily clinics for patients' evaluation and follow-up. Stereophotogrammetric devices are the most used tool to perform these analyses. Although these devices are accurate results must be analyzed carefully due to relatively poor reproducibility. One of the major issues is related to skin displacement artifacts. Motion representation is recognized reliable for the main plane of motion displacement, but secondary motions, or combined, are less reliable because of the above artifacts. Model-based approach (MBA) combining accurate joint kinematics and motion data was previously developed based on a double-step registration method. This study presents an extensive validation of this MBA method by comparing results with a conventional motion representation model. Thirty five healthy subjects participated to this study. Gait motion data were obtained from a stereophotogrammetric system. Plug-in Gait model (PiG) and MBA were applied to raw data, results were then compared. Range-of-motion, were computed for pelvis, hip, knee and ankle joints. Differences between PiG and MBA were then computed. Paired-sample *t*-tests were used to compare both methods. Normalized root-mean square errors were also computed. Shapes of the curves were compared using coefficient of multiple correlations. The MBA and PiG approaches shows similar results for the main plane of motion displacement but statistically significative discrepancies appear for the combined motions. MBA appear to be usable in applications (such as musculoskeletal modeling) requesting better approximations of the joints-of-interest thanks to the integration of validated joint mechanisms.

1. Introduction

Gait analysis is a common tool used in daily clinics to evaluate patient's functions, to help diagnosis and to assure follow-up after medical interventions related to various disorders (e.g. stroke, Parkinson disease, cerebral palsy, ...). Stereophotogrammetric devices, using reflective markers set on the subject's skin, are the most popular tools used to perform such analyses [1]. The accuracy of these devices is excellent with respect to the position of the markers in 3D space [2]. However results must be carefully interpreted because accuracy of such systems is still controversial due to the error induced by marker placement [3,4]. Another major issue related is the skin displacement during the motion causing artifacts. Motion representation is recognized reliable for the main plane of motion displacement; secondary motions however are less reliable because of the above artifacts [5] and due to misrepresentation of joint axes. Secondary motions are therefore rarely considered in clinical reports [6] and not include in modeling research while there are important in clinics (e.g. hip rotations are considered for femoral rotation surgery). Several methods have been developed in order to tackle these problems such as advanced joint model [7] or soft tissues artifact models [8]. Model-based approach (MBA) combining accurate joint kinematics and motion data was previously developed based on a double-step registration method (inverse kinematic approach) and both in vivo and in vitro biomechanical studies [9] for human motion data reconstruction by a scalable registration method for combining joint physiological kinematics with limb segment poses. The method allows fusing validated joint kinematic information with motion analysis data. The primary purpose of this study was to assess the validity of

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lower limb kinematics calculated using a previously published MBA and compared to the kinematics obtained using the widely used Plug-in-Gait method (PiG).

2. Methods

Thirty five healthy subjects participated to this study (height = 178 ± 9 cm, weight = 71 ± 15 kg, age = 24 ± 2, 12 woman). This study was approved by the Ethical Committee of the Erasme Hospital (CCB: B406201112048) and written informed consent was obtained from all subjects prior to participation in the study.

Gait motion data were obtained from a stereophotogrammetric system (Vicon, 8 MXT40s cameras, Vicon Nexus software, frequency: 100 Hz). Subjects were equipped with 20 reflective markers, 16 of them were used for the PiG model (lower limb) and 4 additional markers (medial condyles and malleolus) were added for the MBA (Fig. 1). Mean and maximal distances between the different markers for both methods are presented in Supplementary Material. All reflective markers (except the PiG wands located on the thigh and shank) were set on anatomical landmarks following strict palpation definitions [10]. For the MBA, the wand markers placed on the thigh and on the shank were not used, axis of the MBA joints are strongly defined by selected generic model.

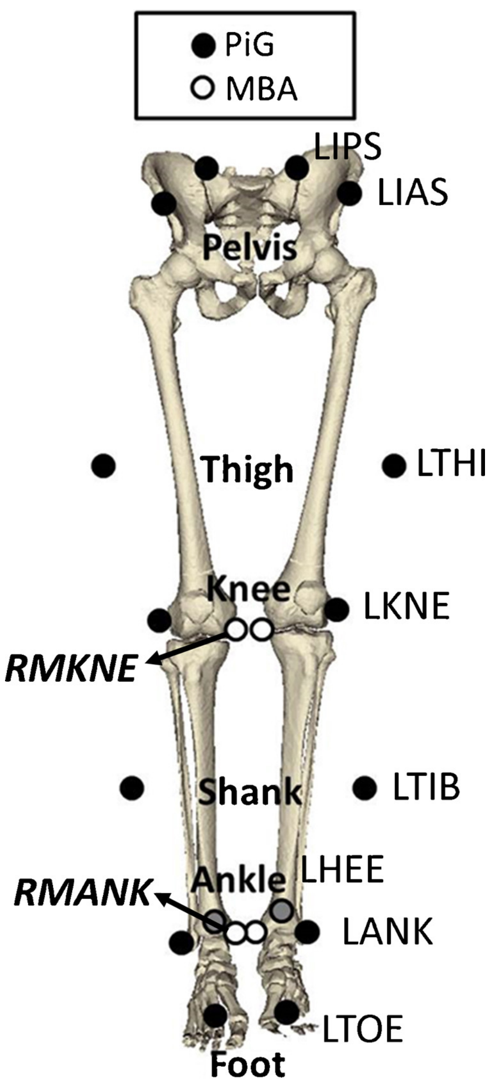

Fig. 1. Markers used for PiG (in black) and for the MBA (same as PiG model plus the four displayed in white). PiG markers are placed on the following bones' landmarks: R/L-ASI (anterior superior iliac spine), R/L-PSI (posterior superior iliac spine), R/L-KNE (lateral epicondyle of the knee), R/L-ANK (lateral malleolus), R/L-TOE (second metatarsal head), R/L-HEE (on the calcaneus at the same height as R/L-TOE) and four markers that are not placed in regard of bony landmarks: R/L-THI (over the lower 1/3 surface of the thigh), R/L-TIB (over the lower 1/3 of the shank). For the MBA the four additional markers (bold and italic) are: R/L-MKNE (medial epicondyle of the knee), R/L-MANK (medial malleolus).

Two trials were recorded for each subject in a gait corridor (length: 10 m). Subjects were asked to walk at self-selected speed. For each subject, all available gait cycles were normalized (between two successive heel strikes) from these two trials. Each trial was processed using the PiG model (available from the Vicon Nexus software [11]) and using the previously described MBA model [9]. Motion representations were similar for the MBA and PiG results [11].

For all available degrees-of-freedom (DOFs), range-of-motions (ROM) were computed (ROM = maximal value − minimal value) for the pelvis, hip, knee and ankle joints. Kolmogorov–Smirnov tests were used to assess data normality. As data were normally distributed, parametric tests were used. Difference between PiG and MBA were then computed. Paired-sample *t*-tests were used to compare both methods. The level of significance was set at $p < 0.05$. Normalized root-mean square errors (NRMSE) were also computed (NRMSE = (RMSE/ROM) × 100) to estimated residual difference between the models. Shapes of the curves were compared using coefficient of multiple correlations (CMC).

Data were plotted and compared with a set of data of a normal population 165 healthy adults provided by the Gillette hospital (provided as supplementary material in a paper presenting the Gait Deviation Index [12]) to be sure that our results are representative for a normal population.

3. Results

Results are presented in Table 1 and Fig. 2 summarizes the average for all subjects for both methods. During gait, the main motion displacements are performed along the sagittal plane (flexion–extension). No difference was found between the PiG and MBA for the main plane of motion during gait: NRMSE values were low (1% for hip and knee flexion, 3% for ankle dorsal/plantar flexion and 2% for anterior/posterior pelvis tilt). CMC were high (0.99, 0.92, 0.97, and 0.89 for pelvis, hip, knee and ankle respectively). These results were also within the normality range of Gillette hospital data.

Some associated motions showed significance differences (3° for pelvis rotations ($p = 0.008$), 5° for knee rotations ($p = 0.014$) and 4° for ankle adduction–abduction ($p < 0.001$)). NRMSE values varied between 10% and 32% depending on the joint and planes. All CMC were above 0.65 for the studied joints.

4. Discussion

Due to markers displacement (soft tissues artifacts) and palpation errors, results of motion analysis performed with marker based system should be interpreted with caution especially for combined motions [13], and are only reproducible for large ROM [14]. According to this study, the proposed MBA [9] and PiG results are similar for the main plane of motion for pelvis, hip, knee and ankles.

Concerning coupled motions, statistically significant differences were found for ROM. NRMSE present high values (between 10 and 32% of motion amplitude). Motion curve shapes also showed differences (Fig. 2 and CMC values).

Coupled motions are relevant during gait analysis since some pathologies induce functional disorders limited to coupled motions only [14]. It is therefore important to obtain reliable information on coupled DOFs.

Although PiG model is widely used in clinics it appears that, due to problems mentioned above, results of some coupled motions do not appear to be fully physiological from a biomechanical perspective. This study does not allow us to determine whether the MBA method is superior or not compared to the PiG model in