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Sensitivity analysis of human lower extremity joint moments due to changes in joint kinematics

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ABSTRACT

Despite the widespread applications of human gait analysis, causal interactions between joint kinematics and joint moments have not been well documented. Typical gait studies are often limited to pure multi-body dynamics analysis of a few subjects which do not reveal the relative contributions of joint kinematics to joint moments.

This study presented a computational approach to evaluate the sensitivity of joint moments due to variations of joint kinematics. A large data set of probabilistic joint kinematics and associated ground reaction forces were generated based on experimental data from literature. Multi-body dynamics analysis was then used to calculate joint moments with respect to the probabilistic gait cycles. Employing the principal component analysis (PCA), the relative contributions of individual joint kinematics to joint moments were computed in terms of sensitivity indices (*SI*).

Results highlighted high sensitivity of (1) hip abduction moment due to changes in pelvis rotation ($SI = 0.38$) and hip abduction ($SI = 0.4$), (2) hip flexion moment due to changes in hip flexion ($SI = 0.35$) and knee flexion ($SI = 0.26$), (3) hip rotation moment due to changes in pelvis obliquity ($SI = 0.28$) and hip rotation ($SI = 0.4$), (4) knee adduction moment due to changes in pelvis rotation ($SI = 0.35$), hip abduction ($SI = 0.32$) and knee flexion ($SI = 0.34$), (5) knee flexion moment due to changes in pelvis rotation ($SI = 0.29$), hip flexion ($SI = 0.28$) and knee flexion ($SI = 0.31$), and (6) knee rotation moment due to changes in hip abduction ($SI = 0.32$), hip flexion and knee flexion ($SI = 0.31$).

Highlighting the "cause-and-effect" relationships between joint kinematics and the resultant joint moments provides a fundamental understanding of human gait and can lead to design and optimization of current gait rehabilitation treatments.

1. Introduction

Human gait studies have been one of the most attractive and challenging areas of biomechanics with different applications for musculoskeletal disorder diagnosis [1–5], therapeutic interventions [6–9] and functional evaluations of different treatments [10–13]. Multi-body dynamics (MBD) analysis has been widely used to study human gait. From a technical point of view, two different approaches of MBD analysis can be found in literature: inverse dynamics and forward dynamics. Inverse dynamics analysis has been mainly used to calculate joint moments, muscle forces and body torques from known joint kinematics [14–18]. On the other hand, forward dynamics analysis has been employed to determine the joint kinematics from known joint moments and muscle forces [19–21].

These studies however have major limitations, which prohibit a holistic understanding of human gait. *First*, MBD cannot provide a systematic investigation of the causal interactions between joint kinematics and the resultant joint moments. Typical gait analyses reveal the effects of joint kinematics on the joint moments and vice versa. However, the relative contributions of individual kinematics to joint kinetics cannot be well evaluated by MBD alone. *Second*, gait studies often do not accommodate the role of inter-patient variability. Large inter-patient variations have been reported in joint kinematics and kinetics [22,23]. However, gait studies are often evaluated for a few numbers of subjects due to the cost and time required for experimental gait measurements.

Due to the cost of experimental data acquisition, principal component analysis (PCA) has been widely used to computationally generate a large population of probabilistic database from a small experimental

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data set. PCA outlines a database through its underlying principal patterns and then enlarges the database via randomizing its major patterns. For example, PCA has been used to generate large probabilistic inter-patient databases of geometry [24], elastic modulus [25] and joint kinetics [26]. Considering the inherent capability of PCA to discriminate and extract the underlying fundamental patterns of a data space, PCA has been also employed to extract and interpret the complicated interactions between highly coupled variables. For example, the relative contributions of joint alignments and loadings to joint mechanics have been investigated through PCA [27]. These two unique capabilities of PCA, enlarging a small experimental database and analyzing the causal interactions, may be hired to address the aforementioned limitations of previous MBD studies. We hypothesized that PCA can computationally produce a large probabilistic database of inter-patient joint kinematics that can be then imported to MBD to compute the corresponding joint moments. In order to perform MBD however, ground reaction forces and moments (GRF&M), related to these probabilistic kinematics, must be first estimated. Previous studies have successfully used artificial neural network (ANN) to calculate GRF&M [34].

ANN is an efficient surrogate model with the ability to *learn* a nonlinear relationship [28–31]. Once a set of inputs (e.g. kinematics) and corresponding outputs (e.g. GRF&M) are presented to the network, the network learns the causal interactions between inputs and outputs. Given a new set of inputs, the trained neural network (surrogate model) can generalize the relationship to produce the associated outputs. A neural network therefore can be of significant advantage, especially when the outputs cannot be directly measured for all sets of inputs. We hypothesized that a trained ANN can be used to estimate the GRF&M related to a probabilistic database of joint kinematics that have been computationally generated through PCA. It is expected that a combination of these computational techniques can address the aforementioned limitations of the previous human gait studies.

This study developed a combined computational framework to provide a thorough quantitative insight into the essential relationships between joint kinematics and joint kinetics. Accordingly (1) a large data set of probabilistic gait cycles was created based on experimental data in literature for which (2) the qualitative contributions of individual joint kinematics to joint moments and (3) the quantitative sensitivity indices of joint moments due to kinematic variations were investigated. The aim of this study was to understand the relationships between joint kinematics and the resultant joint moments with the long term aim of optimizing current rehabilitation methods.

2. Material and methods

A published repository of experimental gait cycles was adopted for the present study (Section 2.1). A large data set of probabilistic kinematics was then created from experimental gait cycles using PCA (Section 2.2). Associated GRF&M were computed using ANN technique (Section 2.3). MBD analysis was then employed to calculate joint moments based on the probabilistic joint kinematics and computed GRF&M (Section 2.4). Once again, PCA was used to determine the contributions of joint kinematics to joint moments (Section 2.5). It should be noted that PCA was used for a twofold purpose: (1) randomizing the joint kinematics and (2) extracting the interactions between kinematics and joint moments. Fig. 1 shows the schematic diagram of the proposed methodology.

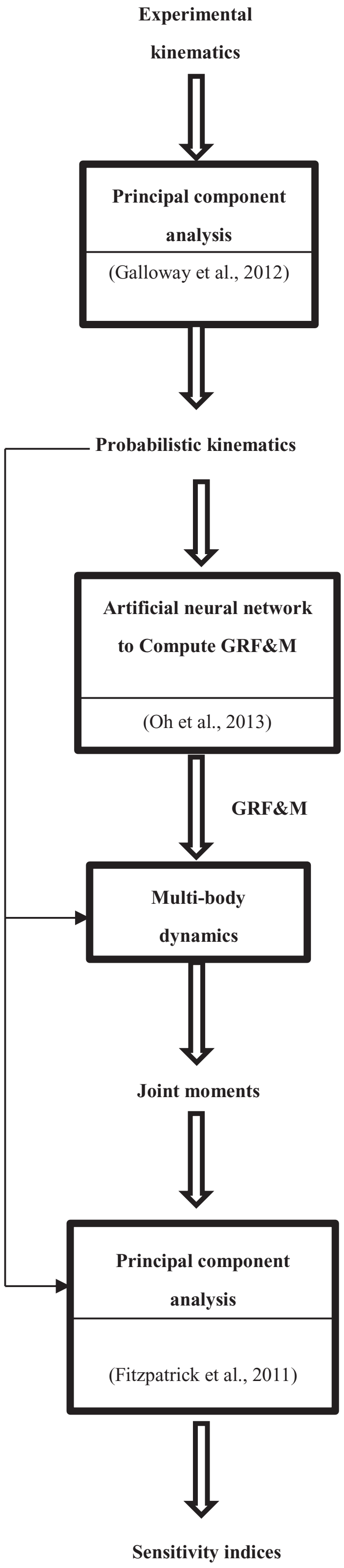

Fig. 1. A schematic diagram of the proposed methodology.

2.1. Experimental gait data

A subject pool consisted of four different participants (three males, one female; height: 168.3 ± 2.6 cm; mass: 69.2 ± 6.2 kg) was adopted from a published repository (https://simtk.org/home/kneeloads). This repository included three dimensional GRF&M (Force plate, AMTI Corp., Watertown, MA, USA), recorded with a frequency of 1000 Hz and marker trajectory data (10-camera motion capture system, Motion Analysis Corp., Santa Rosa, CA, USA) recorded at a frequency of 200 Hz for a total number of 144 gait trials. A modified Cleveland Clinic marker set was used with extra markers on the feet and trunk. These subjects walked with a variety of different patterns which