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Short communication

Human arm posture prediction in response to isometric endpoint forces

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ABSTRACT

The ability to predict the musculoskeletal response to external loads has multiple applications for the design of machines with a human interface and for the prediction of outcomes of musculoskeletal interventions. In this study, we applied an inverse–inverse dynamics technique to investigate its ability to predict arm posture in response to isometric hand forces. For each subject, we made a three-dimensional musculoskeletal model using the AnyBody Modelling System (AMS). Then, we had each subject-specific model hold a weight anteriorly to the right shoulder joint at a distance of half of the arm length. We selected the glenohumeral abduction angle (GHAA) as the only free parameter. Subsequently, we used inverse–inverse dynamics to find the optimal GHAA that minimised a performance criterion with physiological constraints. In this study, we investigated the performance of two different objective functions: summation of squared muscle activity (SSMA) and summation of squared normalised joint torques (SSNJT). To validate the simulation results, arm posture responses to different isometric downward hand forces were measured for six healthy male subjects. Five trials were performed for each loading condition. The results showed that, with an increase in hand load, there was a reduced GHAA in all subjects. Another interesting finding was that self-selected postures for lighter tasks varied more than postures for heavier tasks for all subjects. To understand this, we investigated the curvature of the objective function as a function of the load and observed an increased curvature with increased load. This may explain the reduced intra-subject variations observed for increasing loads.

1. Introduction

Musculoskeletal modelling and digital manikins play critical roles in various fields like orthopaedics (Wagner et al., 2010; Mellon et al., 2013), injury prevention (Ali et al., 2013), ergonomics (Rasmussen and Christensen, 2005a; Nakashima and Komura, 2010; Pontonnier et al., 2014) and industrial design (Rasmussen et al., 2004). However, to reproduce natural kinematics, digital human models must either be driven by experimental kinematics or possess the ability to predict postures and movements. Therefore, we investigate the validity of an optimisation-based musculoskeletal analysis technique to predict the natural human arm posture responses to changes in isometric hand forces. Although the presented case of posture prediction seems to be relatively basic, it contributes to a fundamental understanding of the central nervous system's (CNS) control of human arm postures in response to isometric hand loading.

There are two general computational approaches to simulation of musculoskeletal systems: forward dynamics and inverse dynamics. In forward dynamics, using initial conditions and muscle excitation as input, we integrate the equations of motion to find joint kinematics. In inverse dynamics, we use the kinematic data as input to calculate the joint and muscle forces as output. In some cases, neither side of the equation of motion is known a-priori. This problem can be solved by using an optimisation loop around the conventional simulation model, which can be either forward dynamics or inverse dynamics.

In the inverse dynamics-based formulation, the kinematic degrees-of-freedom are treated as the independent parameters of an optimisation problem. The optimiser identifies these parameters to produce the optimum postural configuration according to a performance criterion and subject to the physiological, anatomical and environmental constraints. This idea was introduced by Rasmussen et al. (2000) and subsequently used by the other researchers (Holmberg and Wagenius, 2003; Maseleno and Hasan,

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2012) under the name "inverse–inverse dynamics". More recently, Davoudabadi Farahani et al. (2014) predicted the kinematics and kinetics of pedalling using this technique, which is also known as Predictive Dynamics (Abdel-Malek and Arora, 2013). The optimality hypothesis in posture prediction is that the postural configurations are selected and planned to optimise a performance criterion. The goal of the present study is to investigate the validity of summation of squared muscle activity (SSMA) and summation of squared normalised joint torques (SSNJT) as the performance criteria in prediction of the glenohumeral abduction angle (GHAA) in response to isometric hand loads. The present case of posture prediction is practically relevant and the predicted results can be validated by conducting a relatively simple experiment.

2. Methods

2.1. Experimental study

2.1.1. Subjects

Six healthy males (age 28.7 ± 1.8 yrs, height: 1.78 ± 0.06 m, body mass: 80.3 ± 4.75 kg) participated in the experiment. All subjects reported being injury free prior to and during the testing period. All subjects were informed about testing procedures, protocols and time commitment and provided their informed consent. The subjects were asked not to consume alcohol the day before the test. The test procedures were approved by the local ethics committee and conducted in accordance with the declaration of Helsinki.

2.1.2. Instrumentation

Reflective skin markers were placed at anatomical landmarks according to Fig. 1. Eight Oqus 1 infrared cameras and Qualysis Track Manager version 2.9 (Qualisys AB, Gothenburg, Sweden) sampled the three-dimensional position of each marker at 250 Hz. The data were collected for a period of 5 s and saved on C3D format. A set of weights (3 kg, 6 kg and 9 kg) were placed to the side of the subjects and used to generate isometric downward hand forces. For each subject, a target point anterior to the right shoulder joint at a distance of half of the arm length from the shoulder was specified by means of a string at shoulder height and an indicator made of a piece of adhesive tape (Fig. 1).

2.1.3. Test protocol

The experiment recorded the arm postures during four loading conditions when the hand was positioned at the target point as shown in Fig. 1. The seated subject was instructed to pick up the weight, touch the target point by the marker installed on the second metacarpophalangeal joint and hold a static configuration for 5 s at each loading conditions. They were asked to keep the wrist and torso motionless. The trials with torso forward bending were excluded from the experiment. One of the loading conditions corresponded to supporting the weight of the arm without any weight (0 N hand force). The order of loading conditions was fully randomized for each subject to make sure that there was no order effect in the data. Five trials were performed for each loading condition. In all trials, the subjects were free to choose their preferred arm postural configuration. There was at least 30 s of rest between the trials to minimise a possible muscle fatigue effect.

2.1.4. Kinematic and kinetic analysis procedures

For each subject, a subject-specific musculoskeletal model was developed in the AnyBody Modelling System (AMS) (version 5. 3. 1. 3556) using the Anybody Managed Model Repository (AMMR) version 1.5.1. The mechanical and mathematical methods behind AMS have been explained in detail by Damsgaard et al. (2006). The measured kinematic data were imported from the C3D file into AMS and smoothed with a low-pass filter (zero-lag, fourth-order Butterworth filter) with a cutoff frequency 10 Hz. These data were processed in AMS (Andersen et al., 2009, 2010) to drive the musculoskeletal model according to Fig. 2. From these models, the subjects' GHAA and the estimated anthropometrics were extracted for later use.

2.1.5. Statistical analysis

A regression analysis was used to statistically demonstrate the significance level of the GHAA variations with increase in hand force across subjects. A value of $p < 0.05$ was used to indicate statistical significance for all tests.

2.2. Computational methods

2.2.1. Musculoskeletal modelling

To predict the GHAA, for each subject, a detailed predictive musculoskeletal model of the experimental setup was built in the AMS (Fig. 3). Each model was then scaled to the corresponding test subject's anthropometric data estimated in Section 2.1.4 and

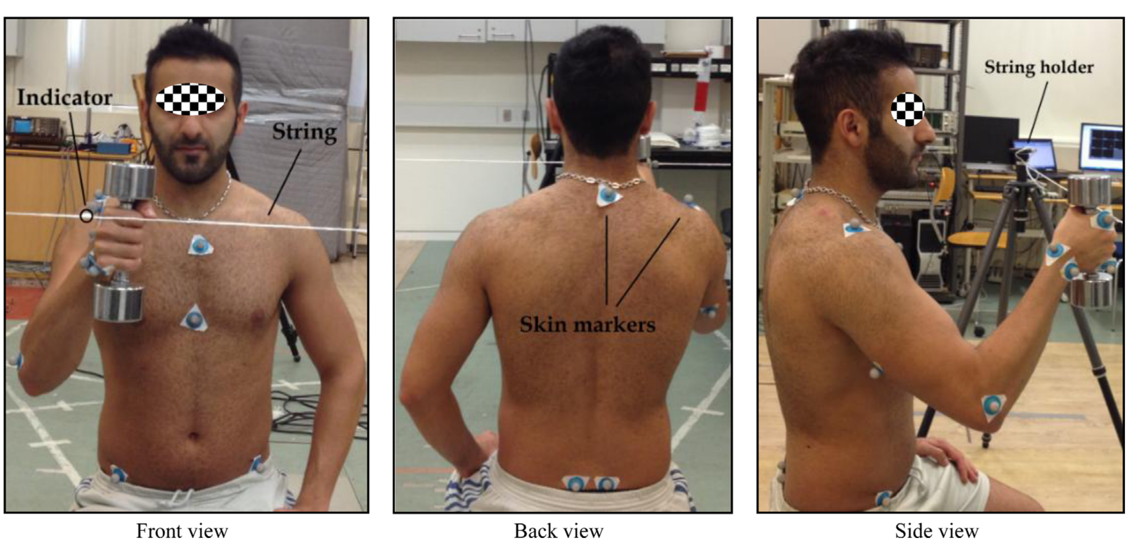

Fig. 1. Illustration of the experimental setup and skin markers placement.