THREE-DIMENSIONAL INVERSE DYNAMICS LINKED SEGMENT UPPER LIMB MODEL IN SWIMMING

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This study aimed to produce a three-dimensional (3-D) inverse dynamics linked segment upper limb model capable of utilising kinematic data of a subject simulating front crawl in air to determine joint rotations and moments. This model is intended to address the current gap in swimming performance literature concerning the measurement of dynamic loads acting on an athlete during swimming. Shoulder, elbow, and wrist joint moments derived from this model are to be used to specify actuator requirements for a biomimetic robotic system which will be used to replicate human swimming technique in future projects.

KEY WORDS: biomechanics, sports, kinetics, robotic simulation

INTRODUCTION: For decades researchers have endeavoured to accurately quantify forces and torques produced by an athlete while swimming (Schleihauf 1979; Takagi & Wilson 1999). The measurement of external forces developed by the upper limbs during the action of swimming relies on accurately capturing the trajectory of a swimmer's arms through water, which describes a complex 3-D s-shape from water entry to exit (Maglischo 2003). Researchers have encountered several challenges when quantifying joint forces and torques during swimming attributed to accurately capturing swimming kinematics in the aquatic environment and quantifying the hydrodynamic forces generated by the upper limbs in dynamic conditions.

Recent work by Ibrahim et al. (2020) demonstrated the validity of an inverse dynamics model driven by orientation matrices for quantifying human movement parameters, particularly joint torques, for land-based sporting applications. Meanwhile, Harrison et al. (2014) coupled an accurate 3-D model of a human swimmer with a Smoothed Particle Hydrodynamics model to quantify the resulting upper limb joint torques during simulated front crawl. Meanwhile, Lauer, Rouard and Vilas-Boas (2016) collected 3-D kinematic data of a subject who was ballasted by a known mass and directed to remaining stationary in water by sculling. Joint moments were then deduced for this activity using a customised inverse dynamics model.

The current study seeks to build on the work completed by the abovementioned sources to estimate upper limb joint torques from kinematic and inertial data of a subject performing front crawl in dry-land laboratory conditions. These results are to be used to specify the mechanical requirements for joint actuators of a biomimetic robotic system which is intended to simulate human front crawl in a wind tunnel in matched dynamic conditions. It is intended that this study provides a step towards addressing the gap in the literature regarding accurate measurement of joint moments and external hydrodynamic forces developed during human swimming.

METHODS: The workflow breakdown for this study is presented in Figure 1. A subject, categorised as a competent swimmer, performed several trials of the front crawl technique in dry-land laboratory conditions at the University of Adelaide. The stroke rate specified for the subject here was derived from the mean stroke count exhibited by high performance swimmers during short distance races (~52 strokes/min) (Pyne & Trewin 2001). A metronome was utilised to provide the subject with an audio cue by which they could maintain their stroke rate. A series of reflective markers were positioned at specific anatomical landmarks about the subject's right upper limb and thorax as indicated in Figure 2. The subject's 3-D kinematic data was collected using a passive marker tracking system (VICON Nexus 2.12, Oxford, UK). Upon completion of data collection, the kinematic data was imported to the custom program built using MATLAB (r2020a, Math Works Inc. US) and was filtered using a second order bi-directional low-pass Butterworth filter and cut-off frequency set to 10 Hz.

Human movement may be considered a function of joint rotations in Euclidean space quantifiable using several mathematical concepts including orientation matrices, Euler/Cardan angles or Quaternions (Cescon et al. 2019; Challis 2020). Here, orientation matrices have been utilised as they are fundamental to sports biomechanics research for providing meaning to the rotation of an anatomical segment/joint in 3-D space and have been used in this way to analyse other human movement patterns (Lauer, Rouard & Vilas-Boas 2016). When described correctly, the orientation matrices provide anatomically meaningful definitions of joint motion e.g., flexion/extension, using the Euler and Cardan angle methods.

The construction of an orientation matrix begins by defining anatomically meaningful coordinate systems for each segment based on the available marker set. A procedure outlined in Zatsiorsky (1998) has been used to construct such axes. The axes and their components defined in the global reference frame (GRF) form the three columns of the 3x3 orientation matrix. The components of angular velocity for each segment may be derived from the diagonal of the 3x3 angular velocity tensor, which is computed by the time derivative of the segment orientation matrix post-multiplied by the transpose of the segment orientation matrix (Berme & Cappozzo 1990).

RESULTS: The inverse dynamics model was used to calculate moments at each upper limb joint. In the interest of clarity, only the calculated shoulder joint moment components are presented in Figure 2. The results effectively visualise the joint torque components during a complete front crawl stroke cycle defined here as theoretical water entry to re-entry for the right arm. It is clear from Figure 2 that the moments in the Y-axis, which represent flexion and extension torque, are the largest when compared to the other two axes.

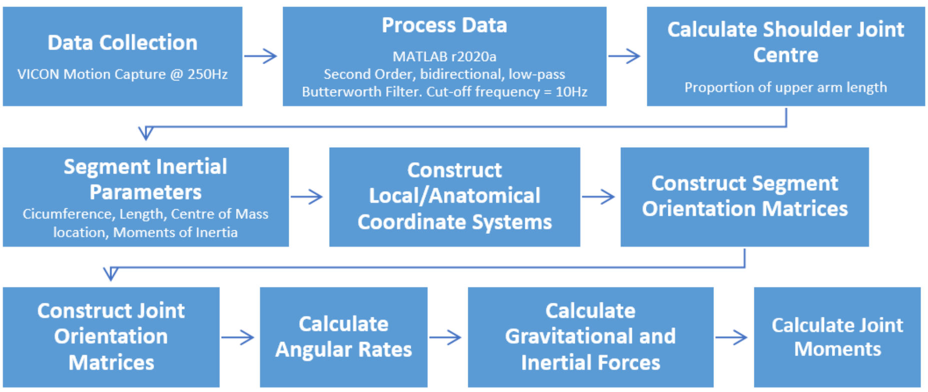

Figure 1: Custom model workflow

The dry-land front crawl exercise is shown to produce peak torque (~$12\ N \cdot m$) at the shoulder at the end of the theoretical underwater phase of the stroke corresponding to shoulder extension. Interestingly, the magnitude of shoulder abduction torque during the start of the theoretical underwater phase is observed to have a considerable contribution to the catch and pull phases. The ranges for joint moments computed using this method are expected to be lower than those experienced in water given the absence of external forces in the inverse dynamic calculation. This is reserved for future work using the robotic system.

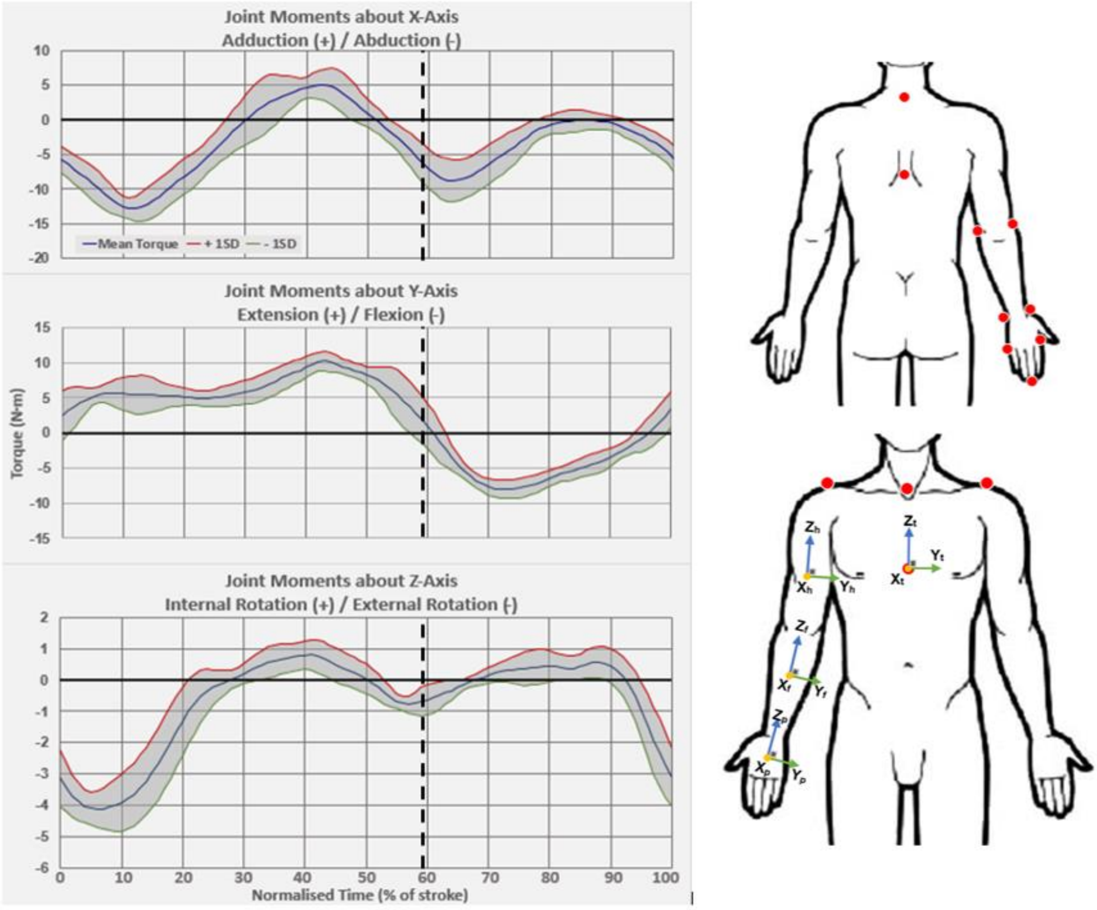

Figure 2: (Left) Joint moments at the right shoulder joint for front crawl in dry-land conditions. 0% and 100% indicate theoretical hand entry. Black dotted vertical line indicates theoretical right-hand water exit. (Right) Indication of reflective marker placement and configuration of Anatomical Coordinate Systems for thorax and each upper limb segment. Axis subscripts indicate the segment e.g., Z_h is the Z-axis of the humerus. Image modified from Ivanov, 2020.

DISCUSSION: The current study was conducted to quantify joint rotations and joint moments during front crawl performed on land. Joint moments calculated here compare well to those calculated by Harrison et al. (2014) although, as expected, the magnitudes of each joint moments are considerably less since this activity was not performed in water. Similarly, the model confirms that the moment magnitude is greatest at the shoulder while lowest at the wrist (Harrison et al. 2014). Indicated in Figure 2, there is a clear indication of where the shoulder transitions from extension to flexion movement towards the arm water exit. The transition from glide to catch after theoretical water entry, whereby the shoulder is in almost full flexion and elbow is fully extended, is clearly indicated. It is interesting to note the magnitude and possible contribution of shoulder abduction torque after theoretical limb water entry, too.

There are a number of attempts to address the gap in the literature regarding the accurate measurement of joint moments during human swimming. This investigation marks only the beginning of a larger research project which aims to contribute new insights on this topic. It is well documented that many sources have developed 3-D biomechanical linked-segment inverse dynamics models which compute joint forces and torques during various sporting activities. However, the purpose of the model developed for this study was to determine joint loads experienced by a human performing front crawl in air to inform upgrade specifications for joint actuators of an existing biomimetic robotic arm e.g., angular rates and torque capacity. The robot is intended to replicate front crawl using real 3-D kinematic swimming data while subjected to conditions in air which match those of water by Reynolds number similarity. This work will build on published investigations by Takagi et al. (2013).

CONCLUSION: This study outlines the initial development of an inverse dynamics model designed to determine upper limb joint torques for a subject performing front crawl in dry-land conditions. Joint moment information derived from the model is intended for specification of mechanical requirements (angular rates and torque capacity) to adequately drive a robotic arm to simulate human front crawl in air with dynamic conditions comparable to water. Orientation matrices were selected to quantify 3-D segment rotation based on existing models in the literature. The model accounts only for moment contributions due to gravity and inertial forces. Scaling this data to matched Reynolds number conditions between water and air is still required. The inverse dynamics model developed for this study is not novel, however, the success of the ensuing research of hydrodynamic force development and joint torque during real swimming is dependent on the results of this study.

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