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**Musculoskeletal modelling in sports - evaluation of different
software tools with focus on swimming**

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Abstract

Previous swim start measurements at *Chalmers University of Technology* involved electromyography (EMG) in order to get an overall picture of the muscle activation pattern during the swim start. In order to fully evaluate sports performance trainers may facilitate additional tools, like videography and force plates, to be able to underpin the feedback given to the athletes. However, the output of the different tools are often complicated and lengthy to handle. Therefore it would be valuable to find an easily applicable tool to visualize biomechanical data. Feedback to athletes based on scientifically measured variables would then ideally be more efficient and effective. This paper evaluates three different software tools regarding musculoskeletal modelling and simulation with quick, meaningful and unambiguous data processing and presentation: *OpenSim*, *BoB* and *AnyBody*. The software package *SWUM* was also analyzed as it is currently the only tool that can model forces and buoyancy during swimming. It has been found that *OpenSim* is a beneficial tool for academic projects as it is freely available and provides a big pool of users and papers available to support the user with additional knowledge. *BoB* is the most straight-forward tool being appropriate for biomechanical teaching and applications where a fast analysis is required. *AnyBody* has the most sophisticated model which can be adjusted to the users demands in great detail and is favorable for investigations with focus on the interaction between the body and the environment or a detailed medical analysis. Great potential lies in the further development and usage of *SWUM* as its basic interface with valuable outputs and simulations as well as the possibility of connecting to *AnyBody* might allow for advancements in swim training.

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1. Introduction

In elite swim races fractions of a second decide on success or defeat. Therefore the analysis of human motion has always been of interest in sports so that swimmers can improve every movement of the race. Musculoskeletal models and simulations driven by previously recorded motion data are nowadays a common method to investigate motion patterns in detail as it has been understood that muscles and joints - the initial units driving the athlete - should be investigated further [1–3]. However, the focus of modelling tools in sports including bones and muscles is only seldomly placed on swimming as numerical simulation in the water environment is demanding [4,5]. Projects like the

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complex CFD crawl model of Keys et al. mainly deal with the flow field around the swimmer and its motion, but do not comprise musculoskeletal modelling [6]. Another study developed a realistic musculoskeletal swimming model driven by neural network activations but do not allow for easy customization of the model [7]. Moreover only some papers discuss the actual usability of these tools for unexperienced persons like trainers and physiotherapists [8].

The work presented in this paper is supposed to be an evaluation of tools regarding musculoskeletal modelling and simulation with application in swimming. It is intended to investigate whether the properties of the different software packages permit individual adjustments regarding posture and environment as well as the data import from various motion analysis modalities used in competitive swim training. This includes videography and force plate data as well as EMG data from a previously conducted study involving the nowadays most common start dive techniques of competitive swimming events [9]. Additionally it will be assessed whether a steep learning curve for new users is achievable and a supporting analysis within a limited time frame is feasible. It is assumed that the application of a visual, scientific tool in swim training can improve training session by making it more versatile and by explaining biomechanical concepts in not only numbers and graphs but also images and videos [10,11].

Besides the usage of such tool may aid in a better understanding of potentially injury causing movements and thereby aid in injury prevention [8,12,13]. As swimmers are predisposed to musculoskeletal injuries like swimmer's shoulder, overuse and fatigue, a visual presentation of their muscle usage is assumed to clarify that a correct, versatile training and a sufficient amount of rest is just as important as the training itself [14,15].

2. Methods

Many tools can be found for a biomechanical analysis of motion capture data in sports. This paper focuses on the applications which encompass a musculoskeletal representation of the human body allowing the evaluation of muscle activations during the observed motion. Therefore three differing tools have been selected. The first one is the plain *Matlab*-based tool *BoB*, the second is the more advanced, widely used freeware *OpenSim* and the third is the purchasable software *AnyBody* which is one of the most detailed and multifunctional tools on the market. In addition to these packages the software *SWUM* is implemented as it provides the essential calculation of fluid forces for modelling in swimming.

All tools have been applied from the first step of converting and inputting motion capture data via the detailed scaling of the model to various analysis procedures. If possible previously captured start dive data from developmental level swimmers was used (*Qualisys* motion capture). In case the number or naming of the facilitated markers did not match the requirements of the software, freely available trial data has been utilized. Additionally forums and direct conversations with the producers have been consulted to gain an all-encompassing insight into the scope of each tool.

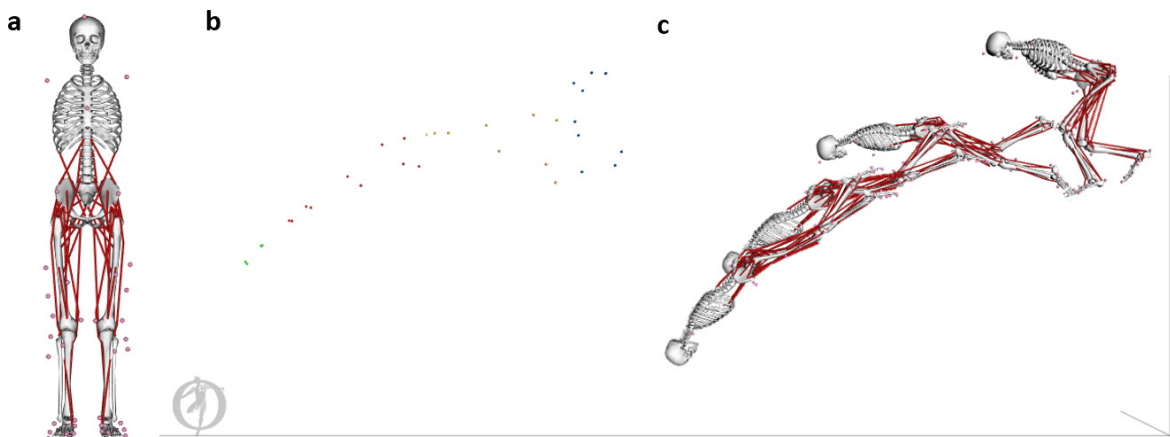


Fig. 1. (a) Lower extremity model of *OpenSim*; (b) *Qualisys* motion capture data from the start jump in swimming imported into *OpenSim*; (c) *OpenSim* model follows the markers after performing the inverse kinematics analysis.

3. Results

3.1. OpenSim

OpenSim is a freely available software package that allows users to build, exchange, and analyze computer models of the musculoskeletal system and dynamic simulations of movement. A muscle model, an analysis, contact models or controllers can be designed from scratch (C++) or already existing models from other users can be scaled to newly recorded movement data for further analysis [8].

Kinematics from motion capture systems can be imported when they have the .trc format [16]. Force plate measurements, center of pressure data or joint angles can be added to the *OpenSim* analysis when they have the .sto or .mot format. EMG can only be imported for comparison with the simulation (.sto or .mot files).

Biomechanical data can be analysed by following certain steps: first the size of a predefined musculoskeletal model is scaled to static marker data recorded for the subject of interest (Fig.1a). The scaling process fits a number of variables like bone and muscle length, the position of the centre of mass of each bone and the mass of each segment (incl. bones and muscles) to the recorded subject [17]. Thereafter the inverse kinematics or inverse dynamics analyses can be performed to calculate joint moments from joint angles and external forces (Fig.1b). Mismatches between the recorded trajectories and the recorded ground reaction forces are minimized by the Residual Reduction Analysis (RRA). Static optimization can then be conducted to further resolve calculated net joint moments into individual muscle forces for each point in time [3]. The whole analysis can then be transformed into a simulation of the complete movement including the muscular activation of the involved muscles.

3.2. BoB - Biomechanics of Bodies

BoB has the most simple and straight forward interface of the three evaluated tools and allows a visual insight into joint contact forces, joint torques, movement trajectories and muscular activation. It consists of 36 skeletal segments and 666 locomotor muscle units. As there is not only one way to use muscles the load distribution is optimized using sequential quadratic programming. Moreover angles, forces, torques, muscle properties or balancing actions can be displayed in videos, graphes or lists (Fig.2). The program runs in *Matlab* and has a simple GUI for parameter insertion and selection of input files [18,19].

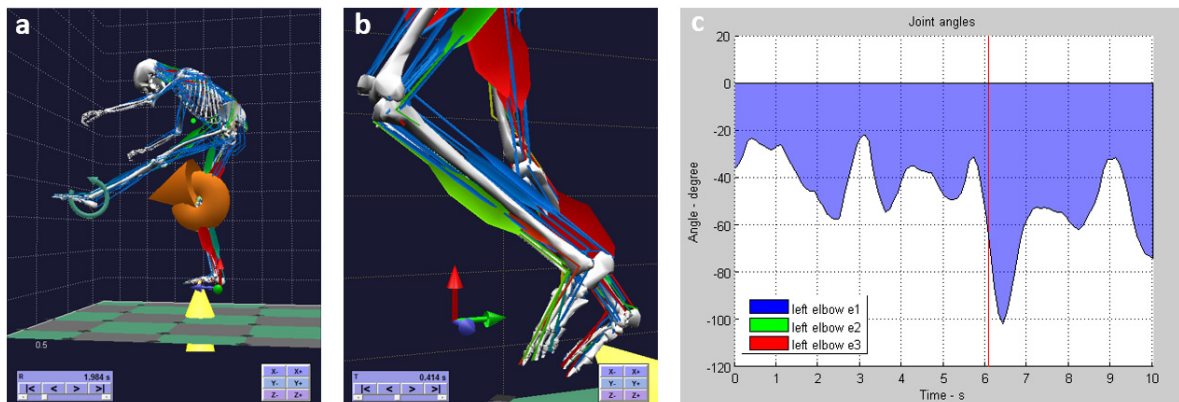


Fig. 2. (a) *BoB* model with highlighted joint torques; (b) Different colours depicting different muscular activity; (c) various graphes can be selected, e.g. joint angles throughout the movement.

The inverse dynamics calculator requires four input files (motion, forces, skeleton properties, muscles properties) and the user defines the duration and time increments of the simulation.

- To define the motion of the model a motion file has to be added (.txt, .csv, .c3d). Each file format requires a certain naming of the anatomical landmarks and a certain number of them, e.g. a .c3d file needs to come with a

30 markers arrangement (*Vicon* naming). *BoB* will run with missing markers but if it cannot find the necessary markers to define the segments on either side of the joint, the joint will not articulate. In case an investigation is lacking markers, the user can create virtual markers by off-setting from real markers (e.g. left front head is 100mm to the left of the right front head) [20].

- External forces or ground reaction forces have to be known and manually inserted into a .txt file (amplitude, speed/frequency, timing, point of application). In case the user does not know the forces the program can approximate the forces to a certain extend.
- The skeleton model (.txt file) can be adjusted to height/weight of the subject that produced the motion file. Possible misalignments of limbs/bones can be modelled as well.
- Information about all considered muscles are stored in a .mat file which can be accessed via the *BoB* interface and different muscles can be added/edited/excluded. The insertion of a new muscle requires all-encompassing knowledge about its geometry, insertion points, force, fibre length, etc.

After inserting the four input files *BoB* will calculate the postures of the model and solve the inverse dynamics problem to determine the loads within the muscles, joints and bones. When the inverse dynamics solver has finished the play button will animate the motion and will allow the observation of the varying muscle activation. The results can be displayed in movies, images, tables or graphs using the output drop down menu.

3.3. AnyBody Modeling System

This software tool is the most sophisticated muscular and skeletal model currently available but has to be purchased. It analyzes musculoskeletal systems as rigid-body systems which allows standard calculation methods of multibody dynamics. The default human model can easily adapted to the users needs (height, weight, segment lengths, strength, bone geometries) and beyond that objects, loads and motion conditions can complement the conditions of the task in question (Fig.3). If the full body model is used 458 muscles are taken into account [21,22].

The environment in the simulation can be modelled (STL format can be imported) e.g. by adding a bike or a gymmachine to the modelling set-up. EMG can only be used as a validation tool, not as an input to drive the model. Interfaces to other software like *SolidWorks*, *Ansys*, *Abaqus*, etc. exist and open up new possibilities. The model itself can be driven by the following inputs:

- motion input can be supplied from .c3d or .bvh files. It is valuable to use a minimum of three markers per body segment. The model requires input from a 3D motion tracking system.
- force inputs
- environmental input (attaching the skeleton to a moving surface)
- synthetic motion by GUI (moving the skeleton by hand)

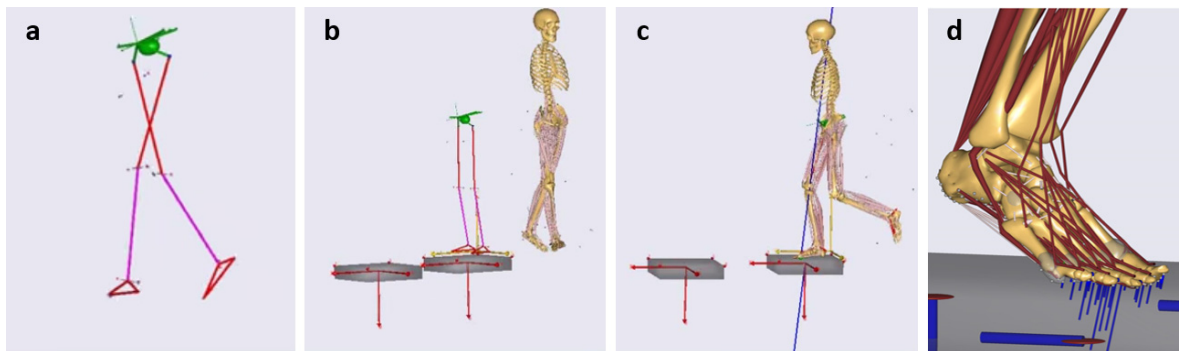


Fig. 3. (a) converting the marker positions into a stick model; (b) scaling the model to the properties of the stick model; (c) combining both models; (d) the *Glasgow-Maastricht foot model* (Source: *Anybodytech*) illustrates the level of detail that can be achieved in *AnyBody*

Modelling is conducted in the *AnyScript* language which is a declarative, object-oriented language. Each model is split into two main sections: the model section (mechanical system, motion, environment) and the study section containing (operations like kinematical or kinetic analysis). *AnyBody* makes use of the inverse dynamics approach and resolves the redundancy problem of muscle recruitment by referring to the central nervous system (CNS). All muscle and joint forces can be determined as a solution to an optimization problem stating that the CNS wants to minimize the load on the muscles. *AnyBody* offers seven different scaling methods where the most advanced one also takes fat percentages into account [23]. Possible ways of using the software are either changing simple parameters (e.g. load, posture) in order to compute the muscular reactions during that task or adjusting one of the existing musculoskeletal motion capture models to a new lab setup by redefining the marker protocol, the availability of force platforms and the lab coordinate system or completely designing a body model and its environment from scratch. This can be beneficial when analyzing animals or unstudied joints or postures.

3.4. SWUM - Swimming human model

The model *SWUM* has been developed to facilitate the musculoskeletal analysis of swimming movements by solving the six degrees-of-freedom absolute movement of the whole swimmers body. It allows the calculation of fluid forces and buoyancy. An investigation like this allows the determination of the ideal swimstroke by maximizing the swimming speed and propulsive efficiency [5,24,25].

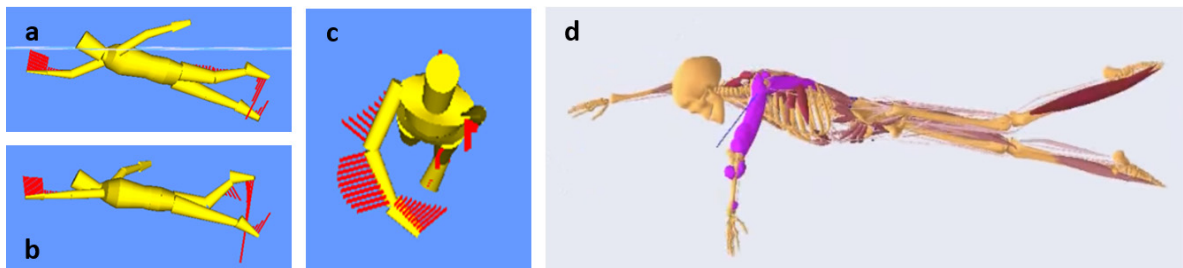


Fig. 4. (a) *SWUM* model illustrating inefficient swimming with a dropped elbow; (b) with excessive kicking; (c) with a straight arm during the catch phase; (d) importing *SWUM* data into *AnyBody* then shows a musculoskeletal model with varying muscle activity levels (Source: *SWUM*)

The user can change the parameter manually in the different scripts. Currently there is no interface to motion capture systems to import motion data. The user has to change the positions of each segment for each frame of the video by changing the absolute angles in the `joint_motion.dat` file. The model is divided up into 21 body segments and each of these segments is again split up into thin elliptic plates. Fluid force are then calculated for each plate from its location, velocity and acceleration. Buoyancy is determined for each quadrangle of an elliptic plate by judging whether it is above or under water. The user can influence the investigation by two means: manual scaling by changing the `body_geometry.dat` file and specification of the analysis parameters in the `analysis_settings.dat` file. Thereafter an analysis can be conducted and an animation can be displayed (Fig.4a,b,c) and different graphs (speed, input power, output power, power efficiency, velocity, etc.) can be shown for the whole body or each segment separately. If desired *AnyBody* files can be generated for musculoskeletal modelling in *AnyBody* (Fig.4d). However, the use of these files in *AnyBody* has only been possible for earlier versions of *AnyBody*.

It has been proven that the results of the *SWUM* simulation were in good agreement with measured EMG activations. However, some muscle activations were unreasonably high and the motion data and EMG data have not been obtained from the same swimmer [26].

4. Discussion

All three observed tools have their advantages and disadvantages, but they are all appropriate for detailed musculoskeletal movement analysis and modelling in the academic environment. The input data and the time available as well as the focus of a project individually determine the best tool.

OpenSim provides different already existing models which can take up any desired posture and motion. Inverse and forward kinematics and dynamics can be realized and the model can also be driven by the CMC tool (computed muscle control). It is freely available and a large community shares experiences, developed code, extended model templates and papers with everyone. However, the data input from motion capture systems has to be converted into the .trc format and for this procedure no software exists. One has to use the scripts of other *OpenSim* users and amend it to tailor it to their application. Additionally the model should be scaled to the body of the analyzed subject in different scaling files (.xml format). *BoB* is a simple tool with a smaller audience which only needs the input of marker positions from a motion capture system and the manual adjustment of some model parameters in a .txt file. Even though the model is valuable for basic analysis of motion (e.g. in sports or ergonomics) it is not advanced and flexible enough for evaluating sensitive medical conditions. The *AnyBody modeling system* is the most sophisticated modelling tool. Many interfaces to other software packages exist and thereby open up further opportunities. A musculoskeletal analysis can be performed under various conditions and with great detail. In order to do so the user has to learn the facilitated modelling language *AnyScript*. In *AnyBody* and *OpenSim* also animal models can be constructed and analyzed which extends the scope of their application. The user has to know the necessary bone geometry (e.g. from medical imaging) and muscular properties for such an application.

It turned out that for all tools a high number of markers as well as an accurate marker placement are vital for an error-free, smoothly moving model. Furthermore in all cases the marker naming during the motion capture should correspond with the naming used in the software used for the successive analysis, otherwise later amendments have to be accepted. Moreover a method for correcting missing or erroneous markers should be kept at hand if a detailed and precise analysis is sought. In addition to the motion capture data the use of force plates is favorable as for many operations ground reaction forces are needed and have to be estimated if not available. It has to be noted that for instance *BoB* does not conduct any filtering of the recorded motion capture coordinates meaning the user has to conduct suitable data pre-processing before using the motion capture data for analysis. Furthermore one can only model the swim start as there is no option for calculating for instance buoyancy. In addition the option of loading measured muscle activity voltage values - besides motion and force data - into one of the tools to drive the musculoskeletal models is not yet available. For that purpose other less visual tools have to be used [17,27].

The modelling tool *SWUM* is quickly understood but it is not possible to import motion capture data. Therefore the user has to define body geometry and the changing position of all body segments manually, which is a lengthy procedure and only an approximation of the actual body motion of a certain swimmer. In addition the model lacks motion constraints which allow impossible movements to be accepted by the simulation. However, the software is capable of visually demonstrating beneficial or faulty swimming techniques as, for instance, arm angles can quickly be changed and their effect analysed.

5. Conclusion

OpenSim is a reasonable tool for academic projects as it is a freeware with many users and papers available to support the user. *BoB* is the most straight-forward tool being most appropriate for biomechanical teaching and general motion analysis. *AnyBody* is the most versatile application which can be adjusted to the users needs in great detail and is favourable for investigations with focus on the interaction between the human and the environment or surgery planning. All three tools are complex and time-consuming which emphasises that simulations are still mainly made for engineering problems and medical decision making and not for an application during time-limited swim training sessions [28]. Nevertheless, promising potential lies in the use of *SWUM* as it is a plain software with the unique feature of modelling fluid forces. Allowing the import of motion capture data to *SWUM* would be a favourable advancement. Renewing its connection to the *AnyBody Modeling System* or even extending its export functions to freeware tools like *OpenSim* would enable swimming professionals with limited software knowledge and small budget to improve their training methods and to facilitate the identification of potentially harmful movement patterns.

However, one has to keep in mind that not all muscular properties including muscle length, contraction velocity, fiber length, contraction history (e.g. fatigue), pennation angle, tendon elasticity and stiffness can be modelled and therefore basic assumptions have to be made (e.g. under all working conditions constant muscle strength). Additionally approximations and errors may occur when connecting motion tracking markers and the computer models. With this knowledge in mind one can apply the discussed software tools and evaluate the outcome of the created models.

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