OPENSIM FULL-BODY MODEL FOR ATHLETES WITH A RUNNING-SPECIFIC BELOW THE KNEE PROSTHESIS

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To date, there is no comprehensive open-source tool to provide movement analysis of athletes using a running-specific prosthesis (RSP) with a below the knee amputation (BKA) to enable the calculation of corresponding inverse kinematics and dynamics. A combination of physical measurements, 2D imagery, 3D motion capture data and geometrical calculations were used to create a musculoskeletal full-body OpenSim model with subject-specific BKA structures. The model was able to reproduce athlete's joint angles and joint moments of the lower extremities while allowing for movement comparison to non-amputee athletes. The model provides a motion analysis tool for athletes with a RSP in an open-source environment, providing qualitatively similar results to previous research, and lays the foundation for more insights into BKA athletes' muscle activity and acting muscle forces.

KEYWORDS: musculoskeletal modelling, prosthetics, long jump, kinematics, kinetics.

INTRODUCTION: The use of technological aids, especially in form of prosthetics, has in recent years become a highly discussed topic as athletes wearing a prosthesis currently even overcome the performance of non-amputee athletes. Yet, the understanding of the underlying biomechanical processes, which might be helpful to explore training potentials or understanding injury mechanisms, is limited compared to the knowledge on non-amputee athletes. Existing research compared kinematic and kinetic differences in athletes using a prosthetics vs an intact limb during various movements (Hobara et al., 2014; Willwacher et al., 2017) and provided an OpenSim model for gait analysis of BKA individuals (Willson & Patrick, 2017). Research on the topic of long jump with and without a transtibial amputation highlighted the influence of their findings on future training protocols and rehabilitation processes, proposing muscle groups, that should be trained to prepare athletes for the unique loading situations of their sport (Funken et al., 2019a). As suggested by the very research group, future studies should tackle the integration of muscle activation or inverse dynamics approaches, which include muscle models for athletes with a BKA. The framework of OpenSim provides an open-source, musculoskeletal modelling software for the calculation of inverse kinematics and kinetics, muscular activity, and muscle force calculations, based on motion and ground reaction force (GRF) data (Delp et al., 2007). Using OpenSim, a full-body musculoskeletal model adapted for athletes with a BKA could reproduce their kinematics and kinetics and predict their individual muscular activity and muscle force history throughout the movement. Thus, contributing to a more precise understanding of the underlying biomechanical processes. Besides the statistical and numerical differences, existing research also showed major distinctions in the used jumping technique, following the given movement restrictions resulting from the prosthetic limb (Funken et al., 2019b). The graphical interface of OpenSim allows for an exact virtual representation of the athletes' skeletal movement, thus making the comparison of the movement and applied technique much more accessible and vivid. The overall purpose of this project, therefore, was to create a framework for future movement analyses of athletes with a BKA, while preparing the baseline structure for additional insights into muscle force contributions and muscular activity during respective sporting activities.

METHODS: The previously collected kinematic and kinetic data from a Paralympic long jumper, wearing the Össur Cheetah Xtreme (Össur, Reykjavik, Iceland) running-specific prosthesis (RSP), was used to create a full-body musculoskeletal OpenSim model for BKA athletes wearing an RSP. The data was collected using a marker based three-dimensional motion capture system (500 Hz, VICON™, Oxford, UK) and a force plate (1000 Hz, Kistler™, Winterthur, CH). Detailed information on the data acquisition can be found in the study by Willwacher et al. (2017). The resulting C3D files were converted to OpenSim compatible files through MATLAB® (R2022b, The Mathworks, Natick, USA). The prosthesis was modelled as the prosthetic blade, with two rigid bodies connected through a ball joint, and the socket, which was connected to the upper part of the blade through a rigid connection (Fig. 1). The RSPs' joint was defined by two markers placed at the medial and lateral edge of the most posterior point of the prosthesis, which corresponded with the RSPs' point of highest curvature. The RSPs' mass and inertial parameters were calculated by virtually dividing the prosthetic blade into nine cuboids and calculating the corresponding relative masses and inertial parameters for each volume, based on an assumed homogenous density and the measured dimensions for each cuboid. The inertial properties of the RSPs' socket were geometrically calculated as a hollow cylinder with known dimensions from marker data on the socket and anthropometric measurements of the athlete's shank. The BKA-specific tibia and fibula were created by adapting generic OpenSim bone geometries. The newly created components were then merged into the generic OpenSim full-body model "Gait3254" (Delp et al., 1990; Yamaguchi & Zajac, 1989; Anderson & Pandy, 1999; Anderson & Pandy, 2001) by replacing the right sided below-knee structures (Fig. 1a). Muscular components of the generic model were maintained for future developments, yet they were not included during calculations of this project. Complementary joints and joint coordinate systems (JCS), fulfilling the connection between the tibia and the socket, the socket and the upper part of the blade, as well as the upper- and lower-blade were included (Fig. 1b). The marker set of the model was adjusted to fit the experimental data, including a full-body marker set consisting of 48 markers placed on all body segments and 28 markers covering the prosthesis and socket. To allow for a comparison of the kinematic and kinetic results between the built BKA model and non-amputee athletes (Fig. 4), two full-body musculoskeletal OpenSim models were adapted to fit the respective non-amputee athletes. The following processing steps were performed with the inbuilt functions of OpenSim on all three models equally. Each model was uniformly scaled based on the 3D marker data of a static standing reference trial and the measured mass of each athlete. Marker data of one long jump trial for each athlete were used to compute the inverse kinematics and corresponding inverse dynamics. Complementary GRFs were applied on the ground contact segment (calcaneus or lower blade) at the centre of pressure. Inverse kinematics were computed with unfiltered marker data, for inverse dynamics calculations the kinematic input data was filtered at 50Hz. Further data processing and visualization was executed in MATLAB®. Joint angles and joint moments were time normalized to the take-off steps' stance phase duration. Stance phase initiation and end were defined trough a vertical GRF threshold of 15 N. External joint moments were described in the coordinate system of the distal segment and normalized to the athletes' body mass and height.

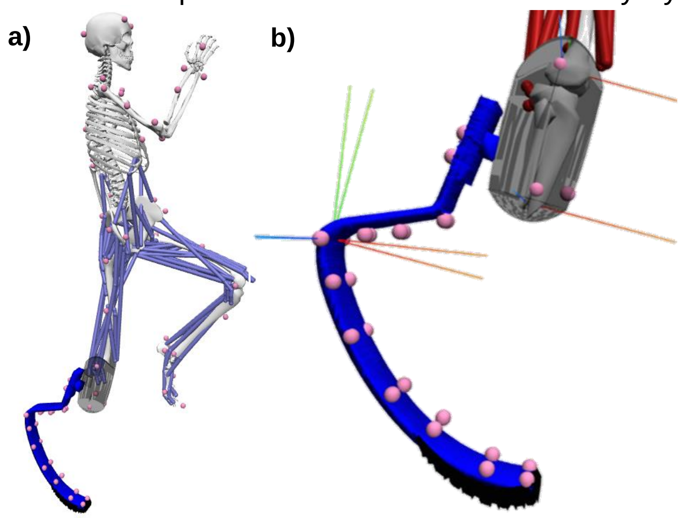

Figure 1: Resulting full-body model (a) and its adapted prosthesis structures with local JCS (b).

RESULTS: Results below relate to the single trial data from the BKA athlete (76.20 kg, 1.80 m), non-amputee athlete 1 (84.07 kg, 1.83 m) and 2 (80.21 kg, 1.81 m).

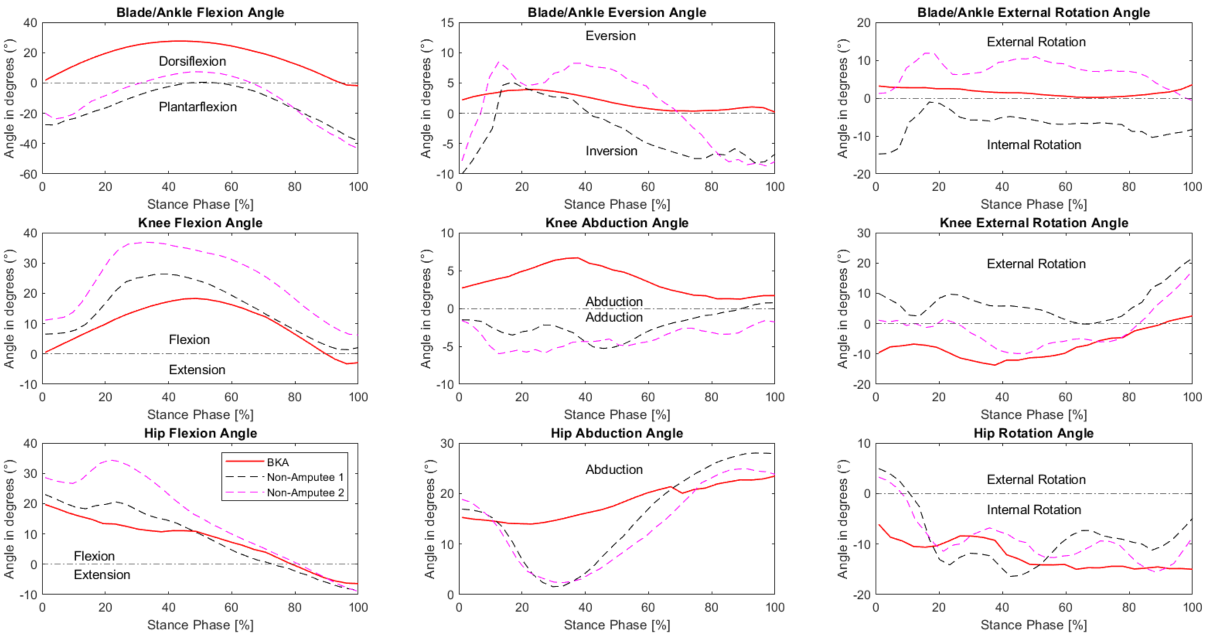

Figure 2: Joint angles during stance phase of the take-off step for ankle/blade, knee and hip in sagittal, frontal and transverse plane.

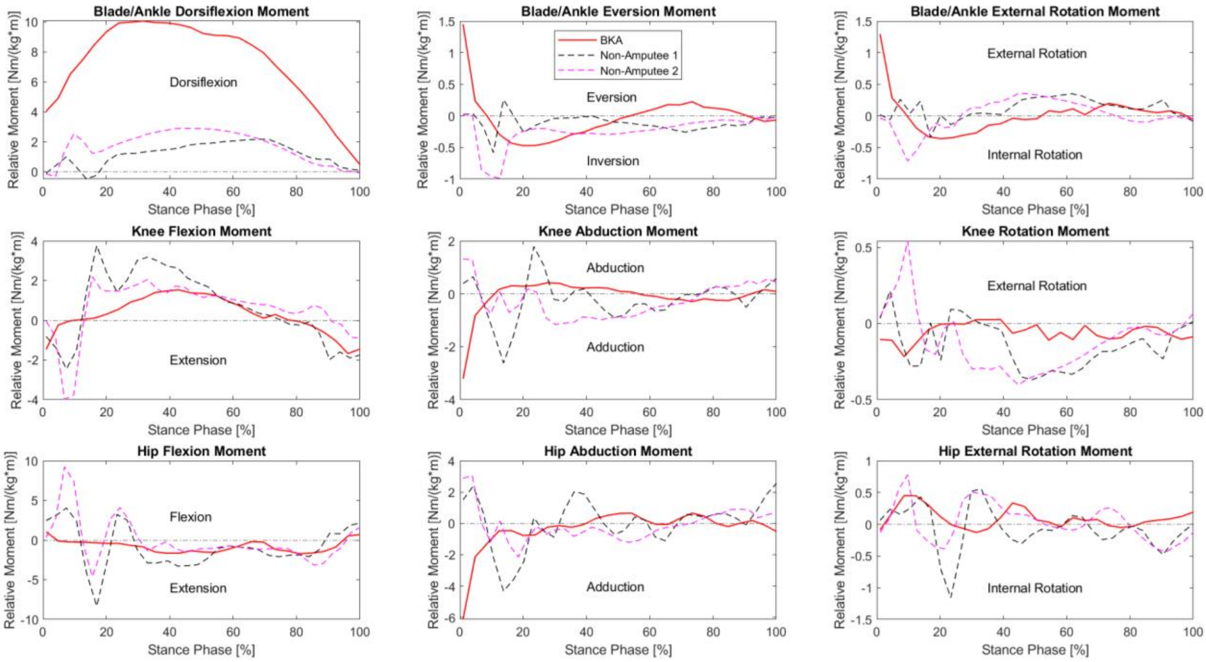

Figure 3: Joint moments during stance phase of the take-off step for ankle/blade, knee and hip in sagittal, frontal and transverse plane, normalized to body mass and body height.

DISCUSSION: The joint kinematics and kinetics resulting from the RSP model show qualitatively similar results to comparable studies (Funken et al., 2019a & 2019b), indicating its ability to substitute the beforehand used frameworks with an open-source alternative. Limitations included the lack of kinematic data from the prosthetic blade during a static, unloaded condition. Providing the BKA specific model, OpenSim enables a tool to compare lower body kinematics and kinetics while its inbuilt user interface visualizes both the skeletal movement and the acting GRFs, as shown for the BKA athlete and non-amputee 2 athlete during the midpoint of the take-off steps' stance phase (Fig. 4). Consequently, variations in the chosen movement strategy and technique, as for the comparison of BKA and non-amputee long jumps (Willwacher et al., 2017), can be made more accessible and connections to occurring biomechanical processes can be represented more clearly.

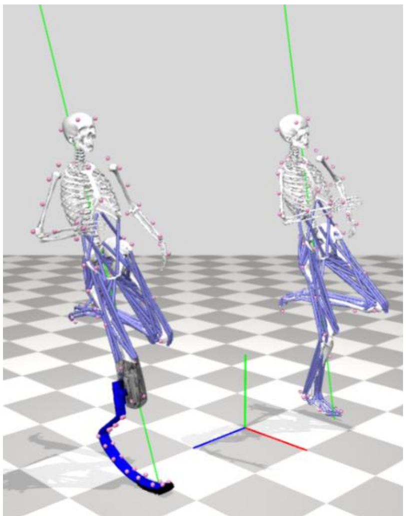

Figure 4: Skeletal movement and technique comparison in the OpenSim interface.

CONCLUSION: This project provided a comprehensive motion analysis tool for BKA athletes using a RSP, settled in an open-source environment, with the ability to calculate joint angles and moments of captured movements. Besides statistical analysis on numerical outputs, the software provides a tool to visually analyse and compare differences in applied jumping techniques between athletes with BKA and non-amputee athletes. As the resulting model is currently restricted to external moment calculations and only provides a framework for the RSP-integration in OpenSim models, future research should tackle the integration of muscular structures, specific to BKA athletes, to allow for precise insights into the athlete’s muscular activity and muscle force contributions during locomotion. Thus, future results might help to gain a deeper understanding of the underlying muscular processes and assess their potential impact on the performance outcome and injury prevention in athletes with a below the knee amputation.

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