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Chapter 11. ESTIMATION OF HIP JOINT LOADS DURING WALKING USING MUSCULOSKELETAL MODELING

11.1. Introduction

Research that examines the biomechanics of the joint has substantial clinical and economic implications for the understanding and prevention of hip diseases. In particular, the hip joint is a subject of great interest due to its vital role in preserving human posture and mobility, and its susceptibility to degenerative conditions [1]. Knowledge of the loads on the hip joint during gait is an important aspect of musculoskeletal research, as it provides information on the mechanics of human movement and facilitates the development of effective treatments for musculoskeletal diseases. However, currently there is no straightforward approach to accurately determine hip joint loads, except through in vivo measurement of contact forces with the use of telemetric implants [2, 3]. Unfortunately, this method can only be implemented by joint replacement surgery, making it invasive. Therefore, a wider implementation of such technologies is currently not possible.

An alternative method for estimating joint contact forces is musculoskeletal modeling. These methods involve the construction of a mathematical model of the musculoskeletal system, which incorporates information on the anatomy and mechanics of the joint, as well as surrounding muscle and ligaments. This model can then be used to simulate walking movements, allowing for the estimation of joint loads and the evaluation of various factors that can influence these loads, such as gait speed, stride length, and body weight (BW). The non-invasive nature of musculoskeletal modeling allows for force calculation with reduced risks and expenses compared to the in vivo

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measurement of contact forces using telemetric implants. Due to its ability to simulate complex movements and evaluate various loading scenarios, musculoskeletal modeling is a powerful tool [4].

Currently, computer software is gaining popularity for modeling the musculoskeletal system to simulate bone-muscle-joint interactions during movements and estimate joint reaction forces. In recent years, musculoskeletal modeling software packages that rely on graphical user interfaces (GUI), such as SIMM [5], OpenSim [6], and AnyBody [7], have become increasingly popular. These packages have simplified the simulation processes and facilitate the development and distribution of new models [8]. To represent the simulated system as closely as possible to reality, the musculoskeletal models should be validated [9]. In order to validate musculoskeletal models, it is essential to compare the results of subject-specific simulations with the experimental in vivo data of the corresponding subject.

One of the commonly applied applications of musculoskeletal modeling is the estimation of the hip joint reaction force (HJF) during different activities [4, 8, 10]. For the development of efficient treatments for musculoskeletal disorders such as osteoarthritis, accurate calculation of HJFs is essential. By providing information on the mechanics of joint loading, musculoskeletal modeling can be beneficial in the development of interventions that target specific loading situations and lower the risk of joint degeneration. Furthermore, the use of musculoskeletal modeling in the estimation of joint loads can provide valuable information for designing prostheses and various assistive devices, as well as for improving rehabilitation regimens.

In general, the prediction of HJF during walking using musculoskeletal modeling is a fascinating area of research that has the potential to have a significant impact on biomechanics, orthopedics, and rehabilitation disciplines. In addition, musculoskeletal modeling can be applied to the design of devices that interact with the human body. These can include equipment such as bicycles, shoes, exoskeletons, training equipment, or orthoses, as demonstrated by Zhou et al. [11], who optimized a shoulder orthosis. Musculoskeletal modeling can provide a more comprehensive understanding of biomechanics and therefore lead to the development of new treatments and interventions for musculoskeletal disorders, ultimately improving the quality of life for those affected.

The purpose of this study was to use the available model to calculate the reaction forces of the hip and evaluate these results.

11.2. Material and Methods

The study used a combination of experimental data and musculoskeletal modeling to estimate HJF during walking. The estimated HJFs were then compared with the in vivo measurements obtained by the use of an instrumented endoprosthesis to evaluate the results.

11.2.1. Experimental data

The experimental data used in the current study were obtained from the publicly available Orthoload database [12]. The data set used in this study was from a single male subject of 61 years, who had a body weight of 75 kg and a height of 172 cm (file 'h2r_150811_2_100'). The subject suffered from osteoarthritis and underwent total hip arthroplasty (THA). This dataset consisted of level-walking kinematic data captured using an optical motion capture system (VICON Metrics, Oxford, UK), force plate data (AMTI, Watertown, USA), and in vivo HJF measurements obtained using an instrumented prosthesis [13].

11.2.2. Musculoskeletal Modeling

Among the range of available musculoskeletal modeling software, AnyBody software (AnyBody Technology, Denmark) was selected, which is a commercial tool, providing a comprehensive musculoskeletal model of the whole body through the AnyBody Managed Model Repository (AMMR). For the analyzes, AnyBody software v.7 with lower extremity musculoskeletal model (AMMR, v.2.4.3) was used [14]. The model consists of the legs and the trunk, which included the head, thorax, and lumbar spine (Fig. 1). The legs are based on cadaver data from the Twente Lower Extremity Model [15].

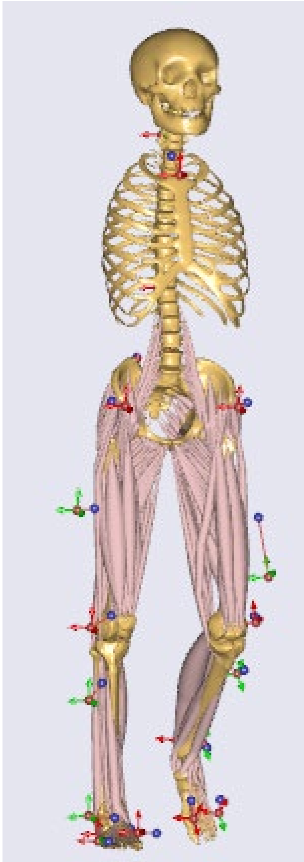

Fig. 1. Musculoskeletal model from AnyBody modeling software with marker set
Rys. 1. Model mięśniowo-szkieletowy dostępny w programie AnyBody modeling z zestawem markerów

The first step of simulation was to specifically-adaped model, which means that it was scaled to match overall anthropometrics and marker data. A patient-specific scaled model, individual joint angles, and force plate data were used as input for the next part of the simulation. To compute joint kinematics, a kinematic analysis was conducted on the basis of the marker trajectories. Subsequently, inverse dynamics analysis was performed to calculate the required muscle activation and forces, as well as the resulting joint moments. Among other things, the components of the force acting on the hip were obtained during the simulation.

11.2.3. Processing of calculated data

After conducting simulations, three reaction force components that act on the left hip joint were chosen for exportation. Subsequently, the data was imported into EXCEL for processing. To ensure comparability, all forces were normalized by the subject's body weight, which was determined to be 75 kg.

The magnitude of the resultant force was calculated based on the three selected components. The resultant force was determined by taking the square root of the sum of the squares of these components. Subsequently, the time-dependent patterns for component forces and the resultant force during the stance phase were plotted, including both calculated and experimentally obtained data.

11.2.4. Comparison with the in vivo measurements

The precision of the predicted HJF and the validation of the simulation results were assessed by comparing the simulated HJF with the in vivo HJF. Comparison was made by visual inspection. Furthermore, the performance of the musculoskeletal model in predicting in vivo hip contact forces was evaluated numerically by computing in the EXCEL software two error metrics as follows:

- Root mean square error (RSME) as a percentage of body weight (%BW), as a global measure of the goodness of the fit. RSME was calculated in the stance phase for the anteroposterior, mediolateral, and vertical components, as well as for the total HJF.
- Pearson's correlation coefficient (R) between the measured and predicted HJFs for the three components of the HJF and the resulting HJF during the entire stance phase. Significance of the correlation was tested with a significance level of 0.05.

Furthermore, the calculated maximum peak value of hip contact force was compared with the results of other studies that used mathematical models to calculate hip contact forces during walking, in order to evaluate the accuracy and reliability of the current model.

11.3. Results and Discussion

The primary objective of this study was to estimate the HJF during walking using a musculoskeletal model and subsequently to evaluate the precision of the calculated forces. Calculations were made only for walking, which is the most reported daily activity. The described data were used for the calculations and the HJFs in stance phase were calculated. Figure 1 shows the model predicted and measured in vivo component hip contact forces and resulting force.

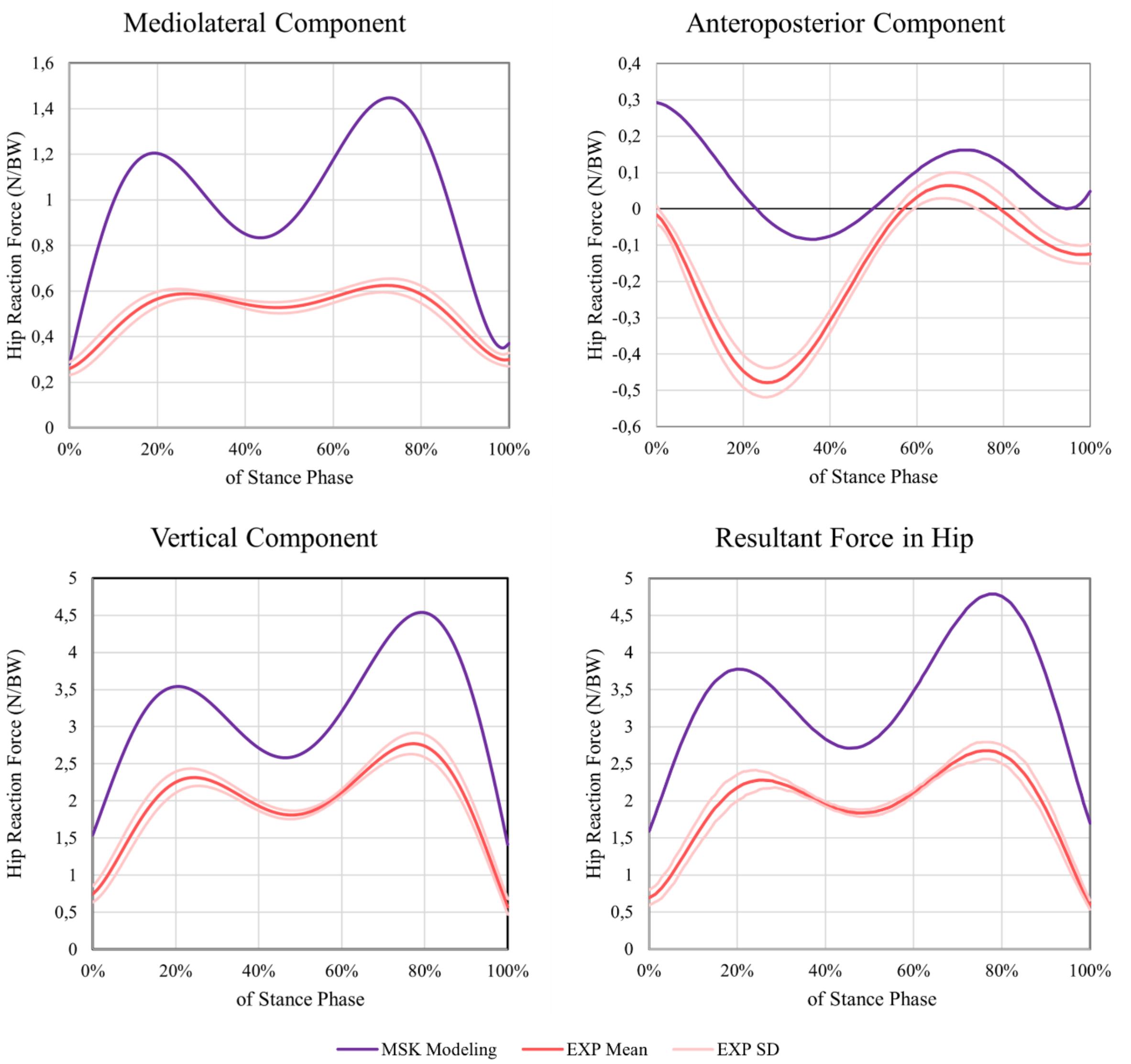

Fig. 2. Measured and predicted hip contact forces in the stance phase of walking
Rys. 2. Zmierzone i przewidywane siły kontaktowe w stawie biodrowym podczas fazy podporowej chodu

The HJF calculated and measured during walking exhibit similar patterns during the stance phase. This suggests that the computational model used in the study captures the general characteristics of hip joint forces during walking. In general, visual analysis indicates that the computational model utilized in this study has the ability to predict the contact forces in the hip joint during walking with a reasonable level of precision. However, there are discrepancies between the magnitudes of the calculated and measured HJF values. The calculated HJF values exhibit a higher magnitude compared to the corresponding measured values. The discrepancies between the magnitudes of the calculated and measured HJF values may arise from limitations of the computational model or measurement errors associated with the instrumented prosthesis.

The maximum resultant force calculated by musculoskeletal modeling is 43.7% higher than the measured in vivo value. This suggests that the model may overestimate the forces acting on the hip joint during walking. This difference may be due to various factors such as measurement error, variability in human anatomy, and differences in modeling assumptions. Typically, a difference of less than 10% between measured and calculated values is considered acceptable in biomechanics research [5]. Studies using instrumented implants have shown that the maximum hip joint reaction forces during normal gait typically range from 2.5 to 3.5 times body weight. However, depending on the condition of the subject, the maximum peak HJFs during gait can reach 4.9 times body weight [2, 16]. Based on these values, the calculated maximum peak resultant force of 4.79 times body weight falls within the range reported in the literature. However, it is at the higher end of the range. It is worth noting that different studies can report slightly different values depending on the methodology and assumptions used, as well as the characteristics of the subject and gait conditions.

The maximum peak value of the resultant force calculated in this study was compared with the results of other works that have used musculoskeletal modeling to estimate hip joint forces during walking. Figure 2 presents a comparison of the results obtained in this study with the maximum peak force values (in Newtons per BW) reported in the selected research.

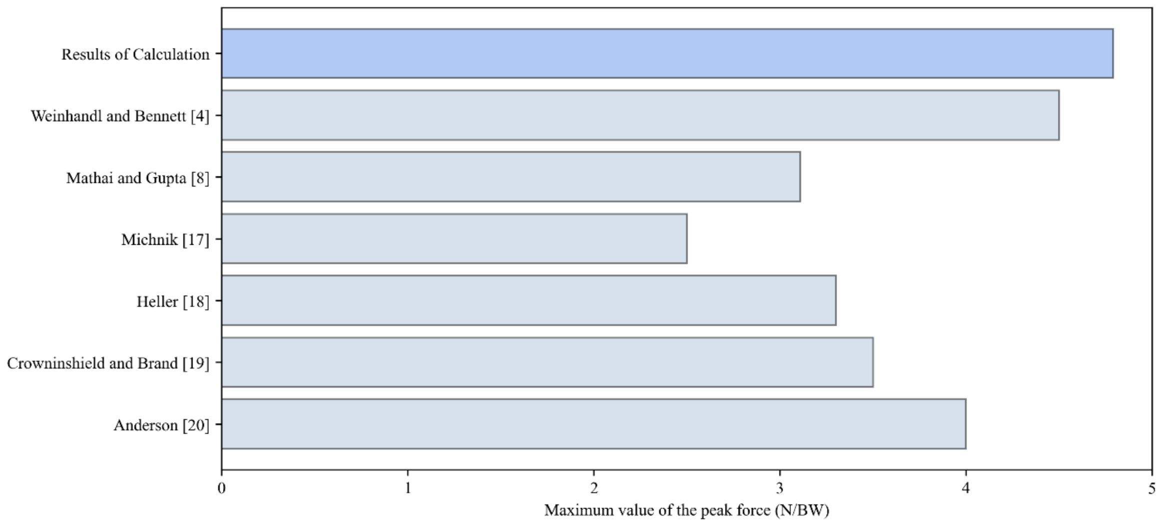

Fig. 3. Comparison of the maximum contact forces of the hip during walking determined by mathematical models
Rys. 3. Porównanie maksymalnych wartości sił reakcji w stawach podczas chodu wyznaczone za pomocą modeli matematycznych

Comparing the maximum peak value of the calculated resultant force with peak values from other works using musculoskeletal modeling for calculations, it can be seen that the peak value of the contact force at the hip during gait calculated in this study is higher than in the other works, with the exception of the work of Weinhandl and Bennett [4], where the maximum value was similar. Differences in results may be due to different modeling assumptions.

Further evaluation of the calculated results included a quantitative assessment, which required calculation of selected error metrics, including the correlation coefficient and the RSME. In statistical analysis, the correlation coefficient represents the degree of concordance between the observed and predicted values, while the RSME is a measure of the accuracy of the prediction. Together, these metrics are used to evaluate the degree of agreement and the quality of the fit between the model predictions and the measured values. The correlation of the HJFs from the musculoskeletal model with the measured values of the HJFs is presented in Table 1, as well as the RSME (in % of the BW).

Table 4

Comparison of error metrics

Parameters	Force Components			Resultant Force
	Vertical	Med-Lat	Ant-Post	
R	0.92	0.89	0.56	0.89
RSME	126.83	52.83	27.54	151.31

The Pearson's correlation coefficient values suggest a strong positive linear correlation between the measured and predicted HJF values in the stance phase for the anteroposterior and vertical components, as well as the resultant force. However, the correlation coefficient for the anteroposterior component of the hip joint contact force was only 0.56, suggesting a weaker positive linear relationship between the measured and predicted values for this component. This may indicate that the model is less accurate in predicting this component of the hip joint contact force during walking, and further improvements may be necessary to improve the accuracy of the model for this component. Overall, these values suggest that the musculoskeletal model is performing well in predicting the in vivo hip contact forces during walking.

The RSME values are quite high, ranging from 27.54% to 151.31%. These values indicate a large percentage error between the predicted and actual reaction force values of the computational model, suggesting potential inaccuracies in capturing the complex dynamics of the hip joint during movement. When comparing the RSME value for the resultant force with the range of RSME values reported in the studies by Weinhandl and Bennett [4] and Mathai and Gupta [8], the 150% value is considerably higher, indicating a wordpoorer accuracy of the model in predicting hip joint forces. This suggests that further refinements may be necessary to improve the accuracy and reliability of the current model.

In general, the calculated hip contact forces in this study were found to be significantly higher than the measured values and data from the previously reported literature. This discrepancy may suggest the need to improve the accuracy of the musculoskeletal model or reconsider the assumptions and input parameters used in the calculations.

11.4. Summary

Estimation of hip joint loads during walking is a critical aspect of musculoskeletal research with significant clinical and economic implications for the prevention and understanding of hip diseases. Invasive techniques, such as telemetric implants, can accurately measure contact forces; however, these techniques are costly and risky. Musculoskeletal modeling, which involves constructing a mathematical model of the musculoskeletal system and simulating walking movements, offers a non-invasive alternative for estimating joint loads. This study used a combination of experimental data and musculoskeletal modeling to estimate the contact forces in the hip during walking. Computational models proved to be valuable tools for predicting contact forces in a human joint, but validation through comparison with experimental data is essential for their accuracy.

The HJFs during walking were successfully estimated and the results were validated using in vivo measurements obtained by the use of an instrumented endoprosthesis. It was found positive correlation between the calculated and measurement data, suggesting potential of the model to predict reaction forces accurately. However, the RSME values suggest the need for further refinement or adjustments to achieve a higher level of precision in predicting the reaction forces of the hip joint. Therefore, further analysis is necessary to identify potential sources of error and refine the model.

The use of musculoskeletal modeling for the estimation of joint loads provides valuable information for the design of prostheses, various assistive devices, and rehabilitation regimens. This research highlights the potential of musculoskeletal modeling as a powerful tool to understand the biomechanics of human movement, develop effective treatments for musculoskeletal diseases, and improve the quality of life of those affected. In general, musculoskeletal modeling is a valuable tool for estimating hip joint reaction forces during daily activities.

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ESTIMATION OF HIP JOINT LOADS DURING WALKING USING MUSCULOSKELETAL MODELING

Abstract

Reliable data on the condition of the musculoskeletal loading of a human joint during daily activities is critical to understanding the mechanics of human locomotion. Currently, the only way to measure joint forces in vivo is by implanting an instrumented prosthesis in patients undergoing total joint replacement. However, this is an invasive method and cannot be performed for all people. Particularly in individuals in whom joint replacement is not necessary, this is not recommended. An alternative means to human movement analysis is musculoskeletal modeling, which uses various musculoskeletal models. In this study, the AnyBody Modeling system model was used for musculoskeletal modeling. The model was customized for one subject based on subject-specific anthropometric data and then used to simulate walking using motion capture data from the OrthoLoad public database. The estimated loadings were compared to the in vivo measurements.

The results showed that the model has the potential to accurately predict reaction forces. However, compared to previous studies, the estimated HJFs were quite high. Estimated forces can be used to develop personalized interventions for gait disorders and also as boundary conditions to develop numerical models of anatomical structures. Furthermore, it can be used to advance our understanding of the mechanics of human locomotion. In summary, musculoskeletal modeling provides a powerful tool for estimating hip joint reaction forces during daily activities.

Keywords: Musculoskeletal simulations, Inverse dynamics, Hip Joint Forces, AnyBody Modeling, Human locomotion, Hip biomechanics