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ASSESSING SCALING AND KINEMATIC ERRORS IN A COUPLED EXPERIMENTAL-COMPUTATIONAL INFANT MUSCULOSKELETAL MODEL

TAMARA T. CHAMBERS*, CHRISTINE D. WALCK*, ERIN M. MANNEN† AND VICTOR A. HUAYAMAVE*

*Department of Mechanical Engineering
Embry-Riddle Aeronautical University
Daytona Beach, Florida 32114, United States
e-mail: chambet2@my.erau.edu

† Mechanical and Biomedical Engineering Department
Boise State University
Boise, Idaho 83725, United States

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Abstract. Musculoskeletal models are valuable tools that enable the study and quantification of biomechanical parameters, allowing researchers to better understand the mechanisms influencing or contributing to human movement. Furthermore, musculoskeletal models have the potential to serve as diagnostic tools for identifying pathologies and disorders, such as developmental dysplasia of the hip. However, current musculoskeletal models are developed using adult subjects, with only a few studies focusing on infant populations, despite the greatest growth rate being in early infancy. Therefore, the objective of this study was to evaluate the impact of multiple linear scaling approaches of increasing complexity on the development of an infant musculoskeletal model. Motion capture technology was used to collect data from the spontaneous kicking movement of a 2.4-month-old infant lying supine. The experimental motion capture data and anthropometric measurements were used to scale the generic gait2392 OpenSim model. Four linear scaling methods of increasing complexity were used: uniform (Uni), nonuniform (Non), nonuniform with knee and ankle joint centers (NAKJCs), and nonuniform with knee, ankle, and regression-derived hip joint centers (NHJCs). Results suggest that the maximum marker errors decreased with the increasing complexity of the scaling approach. The Uni scaling approach resulted in the largest scaling and kinematic errors, with maximum marker errors of 4.92 cm and 5.30 cm, respectively. The NHJCs scaling approach had the lowest maximum marker errors, with errors of 4.17 cm and 4.36 cm, respectively. The scaling method used to develop infant musculoskeletal models should be considered carefully, especially when using linearly scaling generic models developed using adult cadaveric data.

1 INTRODUCTION

Musculoskeletal modeling has exploded in biomechanics research, with OpenSim [1] being the most common open-source tool. Musculoskeletal models are developed to quantify biomechanical parameters that are otherwise difficult or impossible to measure experimentally. There are applications in injury prevention [2–4], in vivo health monitoring [5], clinical outcomes [6–11], and occupational ergonomics [12–14], but most research is focused on the adult population. Few studies have studied human movement in pediatric populations [15–17], and even fewer have studied infants under one year old [18]. The current methods to develop pediatric musculoskeletal models include scaling generic adult models or using medical imaging data (CT or MRI scans) to develop subject-specific models. Scaling adult models does not account for the subject-specific musculoskeletal geometry, and using medical imaging limits research if researchers cannot access these data [15,19,20]. Obtaining imaging data of healthy infants under one year of age is challenging. There are concerns with radiation exposure, subjecting the infants to the uncomfortable conditions required to obtain MRIs (which often require anesthesia), the expense, and the time commitment [14]. Therefore, despite being error-prone, linear scaling is commonly used when developing musculoskeletal models because it is simple and does not require access to medical imaging data.

Incorporating hip, knee, and ankle joint centers into the scaling process can improve the results of linear scaling approaches. It can significantly increase the accuracy of the thigh and shank segment estimates compared to surface markers alone [17]. The knee and ankle joint centers can be estimated using functional methods or as the midpoint between the medial and lateral femoral condyles and malleoli [18,21]. Linear scaling of the pelvis can be improved by incorporating hip joint center (HJC) estimations [22,23], but these HJC locations are difficult to estimate because they cannot be directly identified from surface marker locations. The HJC locations are commonly estimated using either functional estimation methods or regression equations. Functional approaches are implemented during motion capture (MOCAP) for subjects with a sufficient hip range of motion and those who can easily perform the instructed functional movements [22]. However, regression equations are implemented after MOCAP for subjects with a limited hip range of motion [22] or those who cannot perform the required movements. Both approaches are accepted methods of calculating HJC locations when medical imaging is unavailable [24], which is the case for infant populations under the age of one year where MRI/CT is not practical, especially for research purposes.

Few studies have developed pediatric musculoskeletal models, and none of those have investigated the impact of different linear scaling methods on scaling and kinematic errors, as well as kinematic and dynamic results. Therefore, the objective of this study was to evaluate the effect of multiple linear scaling approaches of increasing complexity in the development of an infant musculoskeletal model on simulation errors and predictions.

2 METHODS

The experimental motion capture data were obtained following an institutionally approved IRB [25]. The subject was a healthy, full-term male infant who was 2.4 months old. Lower-extremity movement was recorded over 30 seconds with the infant lying supine. Motion capture technology was used to capture the spontaneous kicking without any external stimulation. A kick was defined as significant movement at the hip joint, exhibiting extension, maximum flexion, and extension again, and was isolated over 3 seconds for each hip [18]. The infant was allowed to move freely and naturally during data collection.

OpenSim [1] was used to develop the musculoskeletal model. The experimental motion capture data and anthropometric measurements were used to scale the generic gait2392 OpenSim model. The process followed is shown in Figure 1. Four linear scaling methods were used to determine their impact on scaling and kinematics errors and inverse kinematics results: 1) uniform (Uni), 2) nonuniform (Non), 3) nonuniform with knee and ankle joint centers (NAKJCs), and 4) nonuniform with knee, ankle, and regression-derived hip joint centers (NHJCs). The Uni scaling approach scales all bodies in an isotropic manner with no virtual markers added. In the Non scaling approach, the femurs and the tibias were scaled nonuniformly in 3 anatomical directions with no virtual markers added. The NAKJCs approach is the Non scaling approach with the addition of knee and ankle joint center markers added to scale the tibias. The NHJCs approach is the NAKJCs approach with the addition of regression-based HJC markers added to scale the pelvis in the medial-lateral direction.

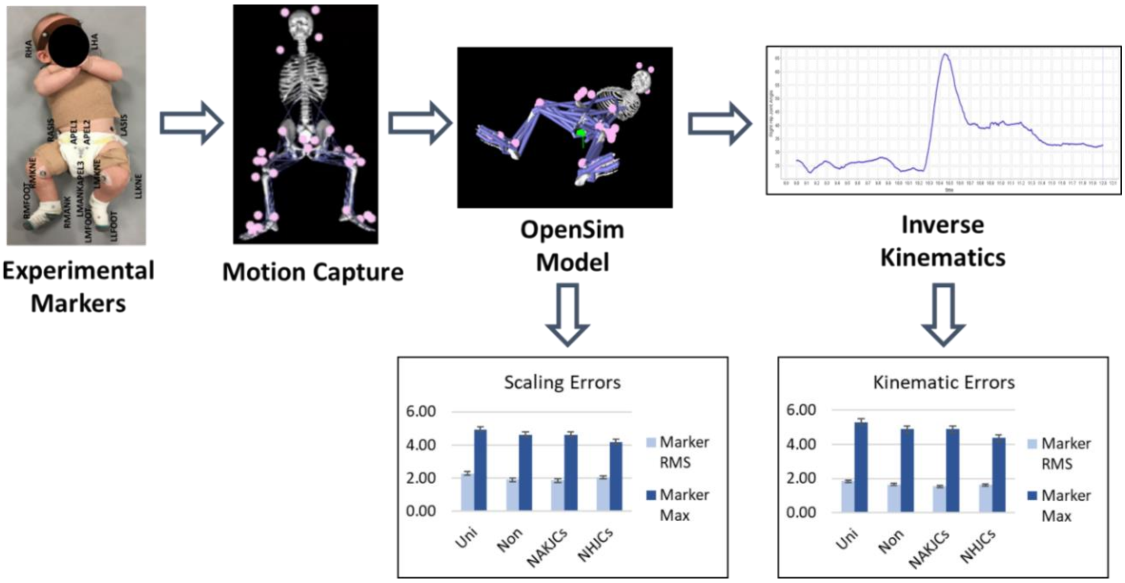

Figure 1: Flowchart of the methods used to obtain the scaling and kinematic errors.

The regression method developed by Hara et al. [26], shown in Equation (1), was used to estimate the hip joint centers for the left and right hip joints, where LL is the leg length. The mean absolute errors for the Hara method are 5.2 mm, 4.4 mm, and 3.8 mm in the posterior-anterior (HJC_x), medial-lateral (HJC_y), and inferior-superior (HJC_z) directions, respectively.

$$\begin{aligned} HJC_x &= 11 - 0.063 \times LL \\ HJC_y &= 8 + 0.086 \times LL \\ HJC_z &= -9 - 0.078 \times LL \end{aligned} \tag{1}$$

In OpenSim, inverse kinematics and inverse dynamics were performed on the scaled models for each scaling method (Uni, Non, NAKJCs, NHJCs). Inverse kinematics was used to estimate hip joint angles by solving a least squares optimization problem to minimize the distance between experimental markers and the corresponding model markers. Inverse dynamics was used to estimate net hip joint moments. Analyses were performed on the isolated 3-second kick for the right and left hips. The total marker error, the maximum marker error, and the RMS errors were recorded for each of the four scaling methods. The maximum and minimum flexion angles and flexion moment values were recorded for the left and right hip joints. The scaling and kinematics results were analyzed to determine the impact of the scaling methods on simulation errors and kinematics predictions. The inverse dynamics results were analyzed to determine the effects of these methods on steps further down the musculoskeletal modeling pipeline.

3 RESULTS

The Uni scaling approach resulted in the largest scaling and kinematic errors compared to the other approaches, with maximum marker errors of 4.92 cm and 5.30 cm, respectively. The Uni scaling approach resulted in the largest RMS scaling and kinematic errors, shown in Table 1 and Table 2. The NHJCs approach had the largest total squared scaling error (1.46 cm), while the Uni approach had the largest total squared kinematic error (1.01 cm).

Table 1: Scaling errors

Scaling Method	Total Squared Error (cm)	RMS Error (cm)	Maximum Marker Error (cm)
Uni	1.457	2.281	4.923
Non	1.038	1.892	4.627
NAKJCs	1.096	1.850	4.628
NHJCs	1.460	2.042	4.173

The kinematic maximum marker error decreased by 1 cm between the Uni and NHJCs approaches. The smallest maximum marker errors were in the NHJCs approach for both scaling (4.17 cm) and kinematic (4.36 cm), while the smallest RMS errors were in the NAKJCs approach for both scaling (1.85 cm) and kinematic (1.54 cm).

Table 2: Kinematic errors

Scaling Method	Total Squared Error (cm)	RMS Error (cm)	Maximum Marker Error (cm)
Uni	1.005	1.830	5.299
Non	0.844	1.650	4.884
NAKJCs	0.803	1.536	4.873
NHJCs	0.976	1.624	4.364

The largest maximum hip flexion angles for the left and right hip joints are in the Uni scaling approach, with 74.1 degrees and 59.4 degrees, respectively, as shown below in Table 3.

Table 3: Inverse kinematics minimum and maximum hip joint flexion for the left and right hips

Scaling Method	Right Hip Flexion (°)		Left Hip Flexion (°)	
	Min	*Max*	*Min*	*Max*
Uni	21.9	74.1	16.3	59.4
Non	11.3	67.0	9.1	54.8
NAKJCs	4.2	57.3	8.8	54.4
NHJCs	1.0	47.0	3.5	46.6

The largest values for the minimum hip flexion angles are also in the Uni scaling approach, with 21.9 degrees (right hip) and 16.3 degrees (left hip). The NHJCs approach had the lowest hip flexion angles for both hips' minimum and maximum values. The right hip has a maximum hip flexion of 47.0 degrees and a minimum flexion of 1.0 degrees. The left hip has a maximum hip flexion of 46.6 degrees and a minimum hip flexion of 3.5 degrees.

Table 4: Inverse dynamics minimum and maximum hip joint flexion moment for the left and right hips

Scaling Method	Right Hip Flexion (°)		Left Hip Flexion (°)	
	Min	*Max*	Min	*Min*
Uni	0.19	0.84	0.06	0.99
Non	0.22	0.85	0.04	1.04
NAKJCs	0.24	0.84	0.03	1.00
NHJCs	0.30	0.85	0.08	1.02

The largest hip flexion moments are in the NHJCs scaling approach for the minimum values for both hips and the Non scaling approach for the maximum values for both hips (Table 4). The largest minimum hip flexion moment values were 0.30 Nm (right hip) and 0.08 Nm (left hip). The largest maximum hip flexion moment values were 0.85 Nm (right hip) and 1.04 Nm (left hip).

4 DISCUSSION

Developing an infant musculoskeletal model in OpenSim can help quantify the internal mechanisms contributing to growth and development within a child's first year. Additionally, it can provide valuable insights into abnormalities in lower limb movements. The objective of this study was to develop an infant musculoskeletal model while evaluating the effect of multiple scaling approaches on simulation errors and the model's biomechanical predictions.

Isotropically scaling the generic musculoskeletal model produced the highest scaling errors, inverse kinematic errors, and hip flexion angles for both hips. The kinematic errors were largely affected by the different scaling approaches. The maximum marker errors for scaling and inverse kinematics decreased as the complexity of the scaling approach increased (Figure 2). The hip flexion minimum and maximum joint angles decreased as the maximum marker errors decreased and the complexity of the linear scaling approach increased (Figure 3). Incorporating ankle, knee, and hip joint centers into the scaling process to improve the scaling of the pelvis, femurs, and tibias (NHJCs approach)

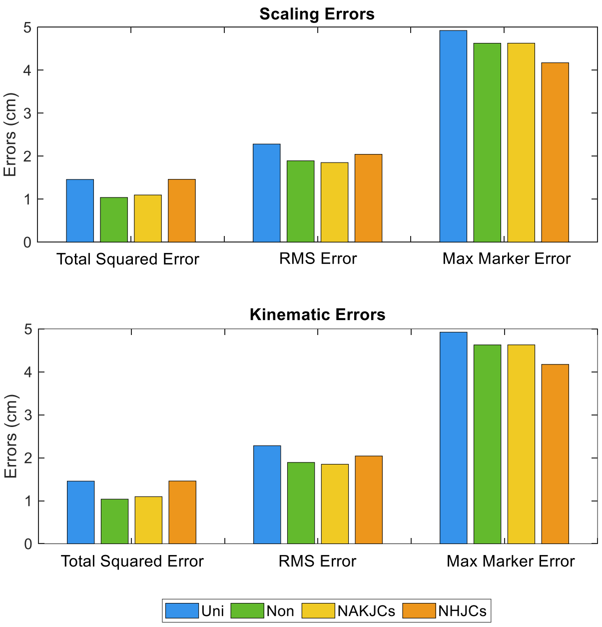

Figure 2: Scaling (top) and kinematic (bottom) errors for the four scaling approaches of increasing complexity from Uni to NHJCs.

produced the lowest scaling and kinematic errors and minimum and maximum hip flexion angles. The kinematics results agree with research showing how hip joint center location errors can affect kinematics in the lower extremity. Kainz et al. [17] studied the gait kinematics of children with cerebral palsy to determine how HJC location errors influence lower limb joint kinematics. The authors reported that when using inverse kinematics in OpenSim, all the joint angles were sensitive to HJC perturbations. They found mean joint angle offsets larger than 5 degrees, which was larger than those reported for healthy adults.

However, the effect of scaling on the hip flexion moments was the opposite. The hip joint flexion moments were minimally affected by the different scaling approaches. The only distinguishable difference was seen towards the middle of the kick for the right leg, as shown in the bottom-left of Figure 3. The minimum hip flexion joint moments increased as the maximum marker errors decreased and the complexity of the scaling approach increased (Figure 3). These results demonstrate how slight changes in the scaling process may lead to large changes in the kinematics results and minimal changes in the dynamics results. This insight is especially a concern when studying pediatric populations or those with hip disorders, such as hip dysplasia, especially since researchers are looking to use musculoskeletal modeling to assist in clinical decision making [27].

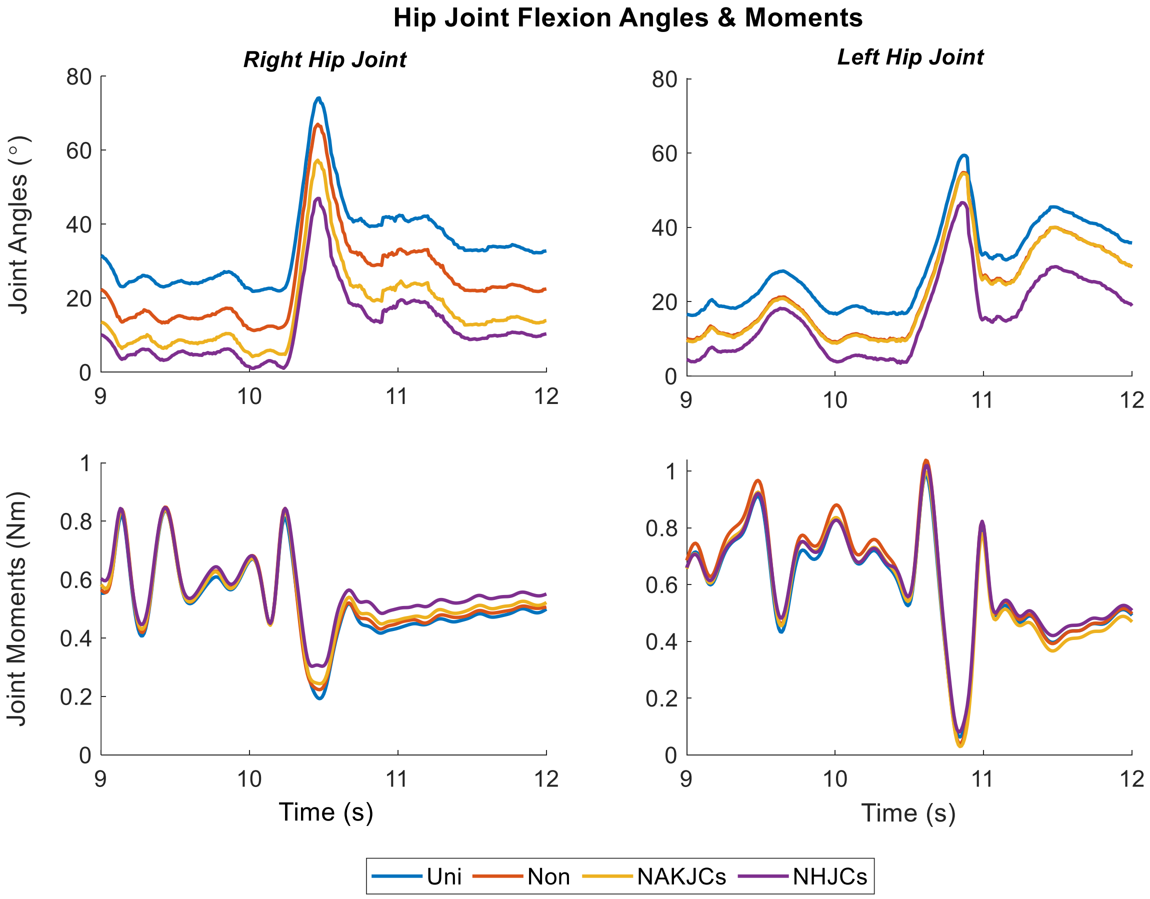

Figure 3: Right and left hip joint angles (top) and joint moments (bottom) for the four scaling approaches of increasing complexity from Uni to NHJCs

There are limitations in this study, such as the regression approach used to estimate the hip joint centers. The Hara method was used to estimate the HJCs in this study. Other researchers commonly use the Bell method [28] or the Harrington method [29] because they provide equally valid results during pediatric gait analysis compared to other regression methods [30]. However, our infant data was limited, so we did not have pelvic depth data since the infant was supine, which is needed for accurate predictions using the Harrington method. Furthermore, Hara et al. had a much larger dataset and demonstrated that the accuracy of their method was comparable with the other regression methods. The authors also found leg length to be the best predictor with no need for additional measurements, such as the inter-anterior superior iliac spine distance. Hara et al. reported comparable mean absolute prediction errors with Harrington et al. [29] and considerably smaller errors than Bell et al. [28] and Davis et al. [31]. Another limitation is using linear scaling to investigate changes in kinematics and dynamics. Nonlinear scaling approaches, such as statistical shape models (SSM), have been shown to improve HJC location estimates compared to linear scaling methods using regression or functional-based approaches [22,32]. Statistical shape modeling is a popular research tool for nonlinear scaling in OpenSim [22]. However, to develop SSMs, researchers need access to medical imaging, which requires subjecting infants to radiation or sedating them.

5 CONCLUSIONS

Developing an infant musculoskeletal model can allow researchers without access to infant data to study factors influencing growth and development within the first year of life. This study evaluated four linear scaling methods of increasing complexity (Uni, Non, NAKJCs, NHJCs) and the effect of these methods on scaling and kinematic errors and biomechanical predictions when developing an infant musculoskeletal model. Inverse kinematics and inverse dynamics tools in OpenSim were used to determine how the kinematics and dynamics changed. The maximum marker errors for scaling and inverse kinematics decreased as the complexity of the scaling approach increased. A trend was identified for the hip joint kinematics results. The hip flexion minimum and maximum values decreased as the maximum marker errors decreased and the scaling approach complexity increased. However, only the minimum joint moment values displayed a trend for the hip joint dynamics results. The hip flexion minimum joint moment increased as the maximum marker errors decreased and the scaling approach complexity increased. The scaling approach greatly impacted the hip joint kinematics predictions when developing the infant musculoskeletal model, whereas the hip joint inverse dynamics predictions were minimally impacted by the scaling approach. When developing musculoskeletal models for pediatric populations, it is essential to consider the scaling method carefully, especially when linearly scaling generic models based on adult cadaveric data. Future studies will investigate the significance of the errors resulting from the four scaling methods and determine how the errors may affect results in subsequent musculoskeletal predictions, such as estimating joint reaction forces and internal muscle forces.

6 ACKNOWLEDGEMENTS

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