The influence of scaling factors and markers' weighting in inverse kinematics for human motion analysis

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Abstract. Motion analysis can produce variability due to inconsistency in anatomical markers placements, which can lead to misdiagnosis and affect treatment outcomes. This study examined the impact of scaling and marker weighting on repeatability when acquired inverse kinematic (IK) assessment. OpenSim was used to inversely transform the motion capture outputs to assess joint angles, hip, knee, and ankle. One young-healthy participant was included, assessed by five raters. Uniform body segments parameters and different weighting schemes (equal, 10, and 100) for targeted virtual markers were set before static and dynamic data examination. Joint angles were then quantified accordingly, while the statistical analysis was used to test variability among raters. Significant differences were observed between all joint angles with equal-weighted and weighted models, particularly for the hip and knee joints. Root Mean Square Error (RMSE) values indicated notable variability in knee joint angles with a shank weight of 100 (20.23°). Hip joint angles also showed high variability across all conditions, while ankle joint angles had lower overall variability but showed moderate increment throughout gait cycle. Although all raters demonstrated strong agreement, the variability introduced by different weighting schemes highlights the need for careful markers' weight selection to minimize error. This study demonstrates that scaling and marker weighting in OpenSim can reduce rater-dependent variability, thereby enhancing the consistency of motion capture analysis.

1. Introduction

In rehabilitation, motion analysis is used as a tool for assessing musculoskeletal and neuromuscular kinetic and kinematic problems, evaluating the effectiveness of assistive devices, and providing recommendations for interventions [1]. However, the application of markers on the skin gives rise to uncertainty, potentially leading to inaccurate results that influence clinical decisions [2]. Numerous studies propose various approaches to minimize errors and reduce variability in results among raters, with the objective of enhancing the repeatability of motion analysis assessments [3–9].

Subject-specific musculoskeletal models offer significant advantages in biomechanical research by providing highly accurate and physiologically relevant insights into human movement. These models, as demonstrated by Sylvester et. al., [10] and Akhundov et. al., [11], are particularly adept at capturing individual anatomical variability, yielding improved estimations of joint and muscle forces, and detecting asymmetries or pathologies that generic models often missed. Other studies used statistical shape models to predict bone geometry and offer the potential to enhance the consistency of clinical gait analysis, reducing variability in inverse kinematics (IK) and inverse dynamics (ID) results compared to linear scaling methods in OpenSim [5]. However, creating these models is more time-consuming than adjusting a generic model to fit a particular subject [8].

OpenSim enables model scaling and marker weighting to minimize errors during motion analysis [5, 6]. Segmental scaling (SS) reduces errors from inconsistent marker placement by adjusting the musculoskeletal model to better match an individual's anatomy and the actual marker locations recorded during motion capture [8]. By customizing the model to the subject's body proportions, SS minimizes discrepancies between default segment sizes and the subject's anatomy, reducing marker placement errors [12]. Another approach is to use a least-squares weighted optimization function to reduce error by assigning different levels of importance to specific markers when aligning the model with experimental data. Markers are given weight based on their significance, with higher-weight markers prioritized to reduce their associated errors. This method helps the model better match the experimental data by focusing on the most important markers, resulting in more accurate joint angles and kinematics [13].

Scaling factors and marker weighting are useful features, commonly used to refine models, to minimize residual error in kinematic and dynamic outcome measures. However, these methods have been relatively unexplored. Baudet and Kadaba et. al., [5, 6] recently

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studied the importance of scaled model and marker's weighting to increase accuracy in lower limb kinematics. This study aimed to investigate the influence of different weighting schemes on IK results, in addition to scaling generic models to gain deeper understanding on how these methods can be used to improve accuracy in motion capture analysis.

2. Methods

2.1. Participants

One abled-body subject (female; body mass; 60.5kg height:1.7m) was included in this study. The subject is young-active student with no current indication of musculoskeletal and neuromuscular disorder. There was no sign and past medical history of musculoskeletal injury.

2.2. Motion Analysis Protocol

The study involved five raters, four of whom were postgraduate students at the University of Auckland. While they did not have prior experience in motion analysis, they underwent training before participating in the study. The fifth rater was a professional with expertise in motion analysis, and these data will be used as base line in this study. A professional applied the markers to the subject using the Contemporary marker setup, a standard method in biomechanical analysis. The subject was then instructed to walk on a treadmill at a self-selected walking speed (SSW) of 1.05 m/s. After each trial, the four remaining raters replicated the procedure on the same subject at least 5-minute intervals to allow for consistency in data collection. The subject continued walking on the treadmill until five distinct data sets were collected. The motion capture was conducted using 13 high-speed Vicon motion analysis cameras (Oxford Metrics PLC, UK) with a motion frequency of 100 Hz, along with an AMTI AccuGait force plate to capture ground reaction forces at 1000 Hz. This setup provided high-resolution kinematic and kinetic data for subsequent analysis (ref: **Figure 1**).

2.3. Post-Processing Data

A static standing trial of the subject in an anatomical position was used as guideline to set-up and label markers on the computational model. This process was essential for model scaling, providing a reference for adjusting the musculoskeletal model to match the subject's body proportions. Contemporary marker sets were applied to mid-segment locations, specifically on the pelvis, thighs, shanks, and feet. Generic model, Gait2354, featuring 54 actuators and 23 degrees of freedom, was used in this study. Compared to Gait2396, this model simplified muscles to improve simulation speed and avoid kinematic constraints by excluding patella and shift insertion of quadriceps to tibia. The default, unscaled version of these models represents a subject that is about 1.8 m tall and has a mass of 75.16 kg, and the model can be modified in OpenSim, an open-source biomechanics simulation application (ref: **2.4.1. Linear Scaling Model**).

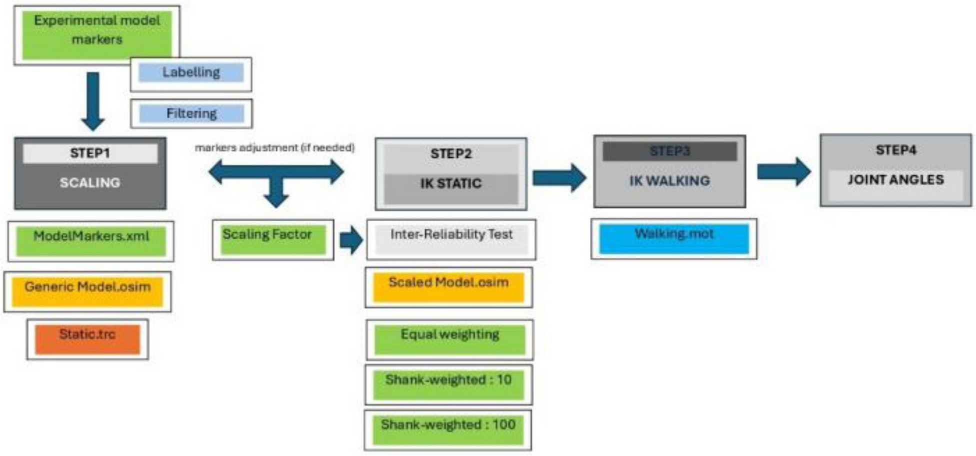


Figure 1. Inverse Kinematic (IK) working flow using standard motion capture systems and OpenSim.

The motion capture data obtained by each rater was converted into c3d files and further transformed into TRC files via motion analysis software for compatibility with OpenSim. It is essential during this process to ensure that the vertical axis in joint coordinate system aligned with OpenSim's coordinate system. Butterworth zero phase low pass filter was used to ensure that the focus remained on normal walking frequency and 6-10 Hz was set to account for normal walking dynamics, excluding the heel strike [14]. Upper limbs, trunk and head markers were excluded in this study and focus on lower limbs.

2.4. Inverse Kinematics

2.4.1 Linear Scaling Model

Scaling process included adjustment in a generic model to match a specific subject using motion capture data. OpenSim's calculate difference in distance of virtual markers between generic model anatomical locations (GrandKneeMarkerSet.xml) and experimental markers (static.trc), see **Figure 2 and 3**. In measurement-based scaling, a single scale factor is computed using one or more marker pairs. For each pair, the distance on the model is calculated in its default configuration, and the experimental distance is averaged across all frames in a specified time range. The scale factor for each pair is the ratio of the experimental distance to the model distance. The overall scale factor is the average of the scale factors from all marker pairs, which can be applied to scale the model along the X, Y, and Z axes or uniformly [8, 12]. This study applied measurement-based scaling and uniform marker weighting across selected marker pairs to provide more standardized approaches, helping to reduce data variability. Upon running IK static pose for both models, it produced values for total square error, RMSE, and maximum error. These differences are validated further through kinematic walking trials.

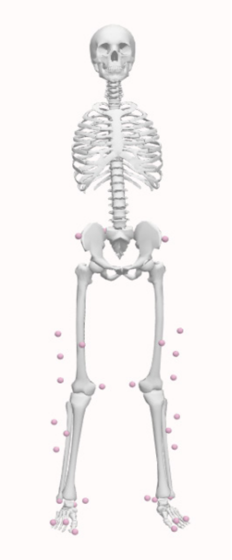


Figure 2. Virtual model markers without measurement-based scaling colored pink.

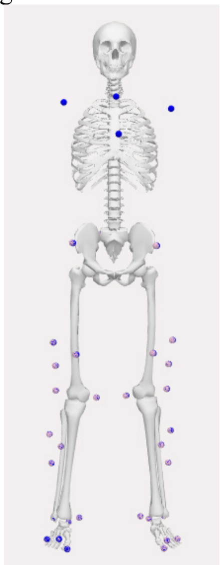


Figure 3. Experimental markers from scaled model (blue) and virtual markers (pink) position.

2.4.2 Marker Weighting

Following the static pose assessment, the operator employed the scaled model to proceed with alternative weighting schemes. However, thigh markers were excluded in accordance with prior research, which indicates that omitting these markers does not introduce additional error beyond that caused by soft tissue artifacts (STA) [6]. A single Degree of Freedom (DoF) was established as a constraint to reduce relative error caused by soft tissue artifact (STA) and kinematic crosstalk [7]. Simplified knee DoF was deemed suitable for clinical gait analysis in determining knee joint angles [6]. The same setup was applied to the ankle joint, while 3 DoF were used for the hip to allow for additional rotational movements; however, only sagittal plane movement was considered in this study. Inverse kinematics (IK) was conducted on a self-selected walking (SSW) trial collected during motion capture, with 10 strides selected from the dynamic data (walking.trc). OpenSim used programming language, ANSI C++, and the graphical user interface is written in Java, allowing OpenSim to compile and run on common operating systems to calculate joint kinematic angles [15], as expressed in this formula:

$$\min_{q}\left[\sum_{i\in\text{markers}} w_i\|x_i^{\text{exp}}-x_i(q)\|^2+\sum_{j\in\text{unprescribed coords}}\omega_j\left(q_j^{\text{exp}}-q_j\right)^2\right]$$
$$\boldsymbol{q_j}=\boldsymbol{q_j^{\text{exp}}}\quad\text{for all prescribed coordinates } j \tag{1}$$

Where $\mathbf{q}$ is the vector of generalized coordinates (e.g., joint angles), $\mathbf{x}_i^{\mathbf{exp}}$ is the position of *experimental marker i*, $\mathbf{x}_i(\mathbf{q})$ is the position of the corresponding *model marker i* (which depends on $\mathbf{q}$), and w_i is the weight associated with marker i [13]. Initially, all assigned markers were given equal standard weighting to analyse the results, which were then compared to trials with adjusted weighting values of 10 and 100. This process was repeated across all raters. Markers on the shank (upper, middle, and lower) were assigned higher weights due to the reduced presence of soft tissue in this region. The differential weighting was intended to minimize error by compensating for the variability caused by soft tissue artifacts in other body segments [13].

Different statistical analysis was employed to assess the error between different marker weighting methods in inverse kinematics (IK) analysis. While comparing the means of equal-weighted method to a series of weighted methods, where shank marker weights are set to 10 and 100. Mean difference and variability of the results in different weighting schemes indicated influence on weighting to kinematic joint angles results.

2.5. Statistical Analysis

In this study, IBM SPSS version 29.0.2.0 (2024) was used to statistically analyse absolute agreement using Inter-class corelation (ICC), accounts for both random and systematic differences between raters, providing more comprehensive evaluation of scaling factor consistency. ICC score was defined as values above 0.90 showed excellent agreement. Similarly, statistical approaches were carried out to validate the significant influence of different weighting schemes on sagittal planar motions on hip, knee, and ankle joint angles, using Wilcoxon non-parametric (p=0.001) methods as data abnormally distributed. ICC was also performed to assess different weighting schemes.

3. Results

3.1. Inter-rater Variability Using Scaling Factor

Scaling factors on all body segment parameters from five raters were assessed, and the average intraclass-correlation coefficient (ICC) of 0.930 demonstrated a high level of reliability of method and agreement among raters. While the F-test (F=13.517, p<.001), with 95% CI [0.794, 0.986] confirmed the statistical significance and suggested that the use of a scaling factor substantially improve repeatability in motion analysis.

3.2. Marker's Weighting and Inter-rater Variability

3.2.1 Lower Limb Joints Angles

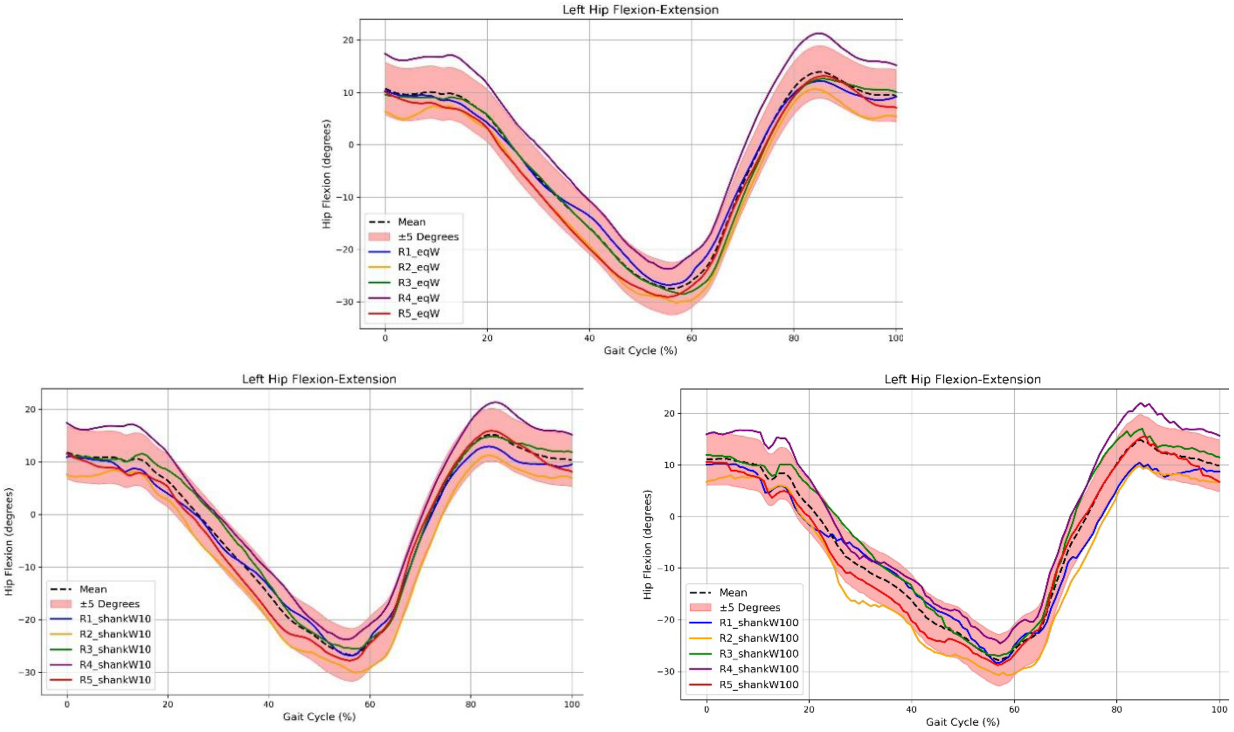
The results from the Wilcoxon Signed-Ranks Test, conducted by five different raters, revealed a consistent pattern of significant differences in joint angle measurements under various conditions, suggesting that weighting has a considerable impact on inverse kinematics (IK) results. For raters 1, 2, 3, and 5, both the 10 and 100 weighting methods significantly influenced IK results when compared to the equally weighted model, with p-values consistently below 0.001 for all joint measurements. In contrast, R4 found no significant differences in the knee and ankle joints between the weighted and equally weighted models, but a significant difference was observed for the hip joint when the shank was weighted 100.

The error in inverse kinematics (IK) for the hip, knee, and ankle joints is generally lower when the shank is weighted by a factor of 10 compared to 100. However, a conclusion cannot be derived directly whether lower weighting overall is more effective. While R^2 remains high, the RMSE variability—especially the large spike in 5th rater (R5) for the hip—suggests that certain weighting schemes or joint-specific models may not perform as consistently across trials, potentially due to factors like sensitivity to weighting differences. Hence further variability testing is needed to determine which weighting method offers the greatest consistency across raters, suggesting the method with less variability will improve the repeatability in IK analysis.

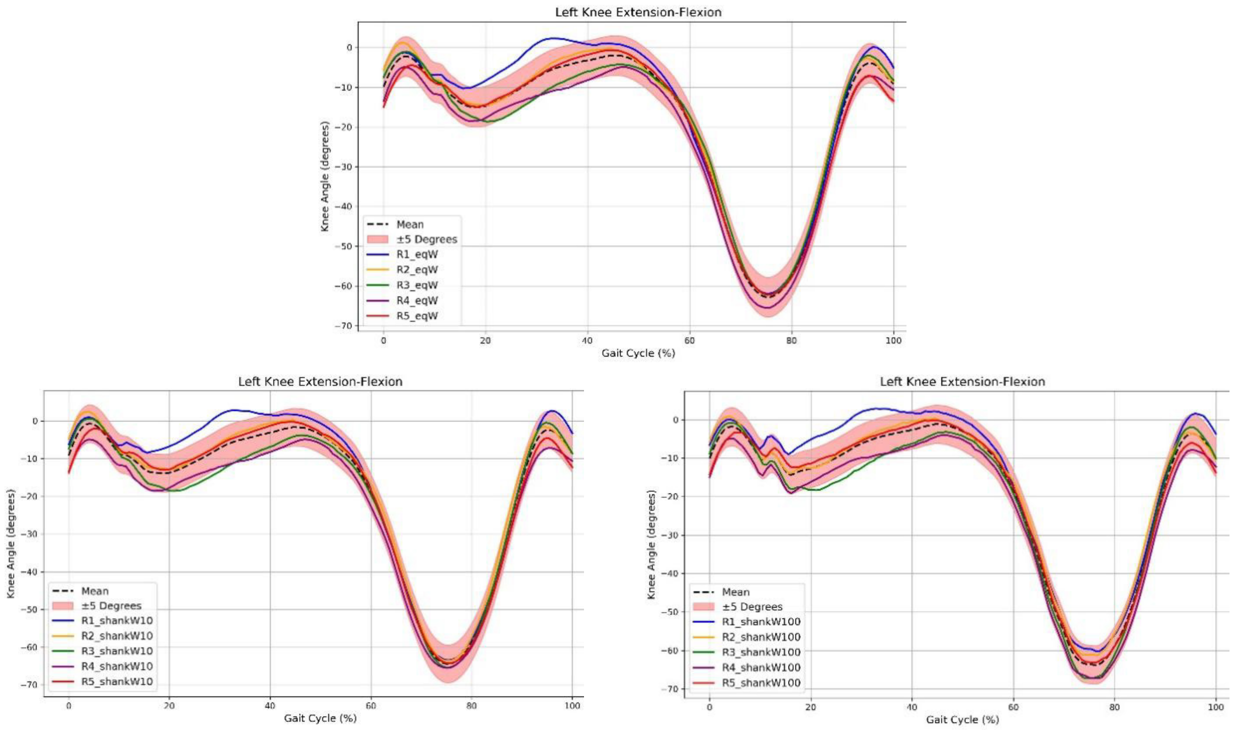
Similarly, the greatest variability in the knee angle, particularly in condition where the shank is weighted at 100, with a mean difference 20.23° and SD 3.0, which is higher than the variability observed in the shank weighted at 10 (19.49°) and equally weighted conditions. The highest variability occurred during mid-gait cycle (around 40–60% of the cycle). Similarly, the hip angle exhibits consistently high variability across all conditions, with a slightly higher joint angle standard deviation in the shank-weighted 100 condition (mean SD 14.86°, 3.7°) compared to the shank weighted at 10 and equally weighted conditions (both joint angles value 14.71°). This variability occurred throughout the gait cycle. The ankle joint angle, although displaying less overall variability, shows a moderate increase in variability in the shank-weighted 10 condition compared to the other two conditions. It generally has lower variability but experiences some spikes around 60–80% of the gait cycle. All the ICC values are above 0.95, which means that there is strong to excellent agreement between the rates for all joints (hip, knee, ankle) in non-specific weighting and under both weighting schemes W100 and W10 (ref: **Table 1.** and **Figure 4.**)

Table 1. Kinematics joint value comparison using different weighted methods

Weighting Schemes	All Equal			Shank Weighting					
				10			100		
Joint	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip
Mean Difference	14.7	19.5	8.5	14.7	19.5	8.5	14.9	20.2	7.9
SD	2.3	2.6	3.3	1.9	2.8	3.0	1.7	3.0	3.7



(a)



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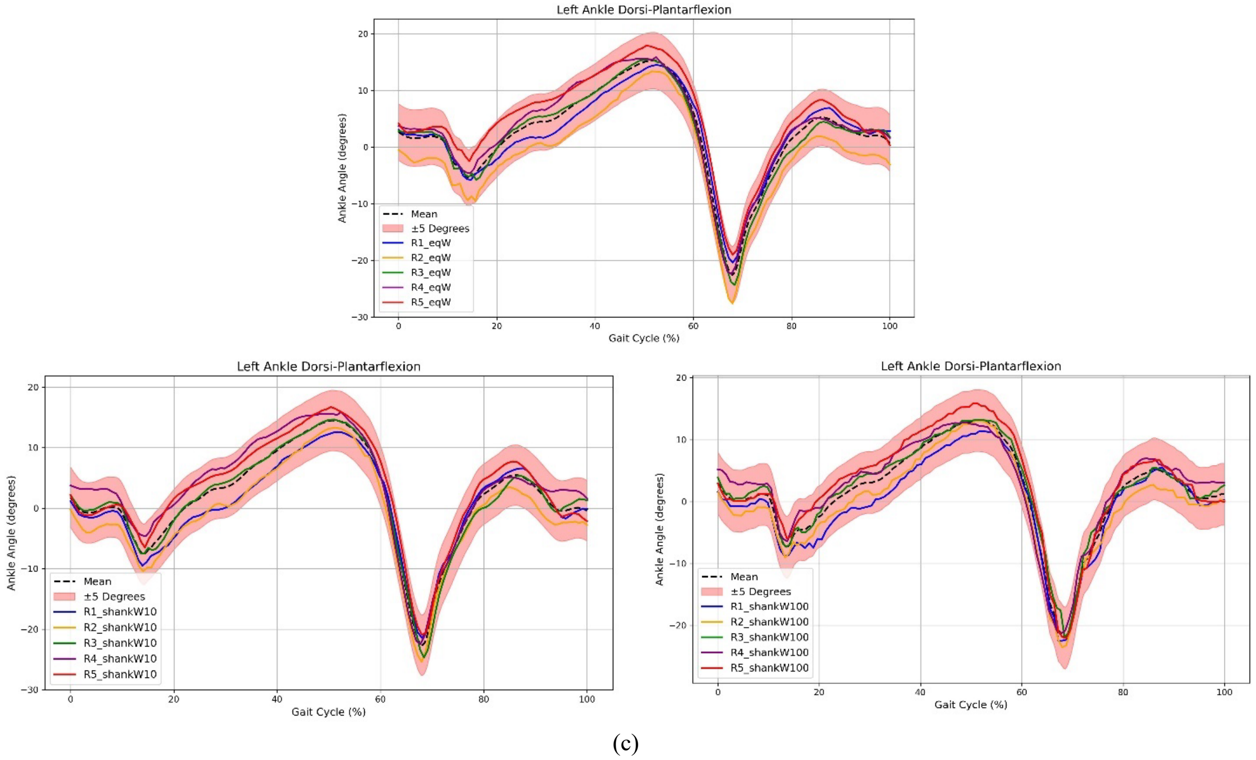

(c)

Figure 4. Inverse Kinematic sagittal plane joint angles variability in all raters of the hip joint (a), knee joint (b) and ankle joint (c) for different scheme; equal weighted (top), weighted the shank by 10 (left) and 100 (right)

4. Discussion

This study investigated the influence of using scaling factors on the model and weighted markers on repeatability when doing inverse kinematics analysis. In OpenSim, the scaling method adjusts a generic musculoskeletal model to match an individual's anatomical dimensions, aiming to reduce errors in Inverse Kinematics (IK) analyses. When the scaling factors determined by all raters were assessed using a two-way mixed-effects Intraclass Correlation Coefficient (ICC) model for absolute agreement, an ICC value greater than 0.90 indicates excellent reliability and consistency among raters. Body segment parameters are the same for all raters, so this finding suggests that marker placement among raters is close to one another, since the dimensions of each body segment in the model are scaled based on relative distances between pairs of markers obtained from a motion-capture system and the corresponding virtual marker locations in the model. When scaling factors are consistent across raters, the adjusted models are likely to accurately represent the subjects' anatomies, leading to more precise determination of joint axes and angles and minimizing the potential for variability due to subjectivity in marker placement [8, 12]

Different weighting schemes in inverse kinematics (IK) analysis significantly affect joint angle variability, with the shank-weighted 100 method producing the highest variability, particularly in the knee and hip joints. Notably, lower weights (shank-weighted 10) and equal weighting provided a better fit and reduced variability in IK results, as evidenced by lower mean differences and standard deviations. Despite the high variability observed in all joint angles when using a shank weighting factor of 100, the inter-rater reliability score remained high (0.95) across all conditions. There was no satisfactory explanation for these differences, although the results suggest that subjects may have altered their movement patterns during walking. Large mean differences in the knee (15°) and hip joints (20°) are predictable, considering the substantial range of motion in both joints—hip flexion-extension (-30° to +20°) and knee flexion-extension (-60° to +5°) during normal gait. This suggests that the variability is still within an acceptable range (mean SD ±5°). Variability in marker placement on the shank can result in high variability especially when it weighted. Graph 2 demonstrated a major discrepancy with Rater 4, where the joint angle values for the hip and knee were consistently much higher than the mean but lower for the ankle. This can lead to significant differences when dealing with small sample sizes. A limited sample size can also contribute to this high variability; as mentioned, at least 13 samples are required to obtain more valid statistical results [6].

Weighting specific markers in IK analysis, such as the shank, aims to reduce errors due to inconsistencies in placing markers on anatomical landmarks and soft tissue artifacts [6, 8, 13]. However, there is no standard or guideline for performing this method to achieve more accurate results. The RMSE and R^2 values showed that weighting the shank by 10 provided results closer to equal weighting methods than weighting the shank by 100, which resulted in higher error. Nonetheless, the error remains relatively smaller than that reported in previous studies, ranging from 0.2° to 9.3°, 1° to 11.5°, and 0.4° to 18.8° for the hip, knee, and ankle, respectively [16,17]. To measure accuracy in motion analysis, the data should be verified with dynamic fluoroscopic x-ray [3,4,18], which is beyond the scope of this study. However, this study demonstrated that weighting specific markers in IK influences joint kinematic results, hence careful selection of markers weighting needs to be considered. Further research is needed to explore the impact of specific joint considerations when choosing body segment pairs to be scaled and weighed.

5. Conclusion

This study highlighted how scaling and weighting protocols in OpenSim reduce rater-dependent variability, improving the consistency and repeatability in motion analysis. By minimizing subjective biases in marker placement and model customization, these strategies enhance the precision of joint angle and kinematic measurements, supporting more reliable biomechanical analyses and clinical decision-making. Additionally, the study shows that different weighting schemes significantly impact joint kinematics, with higher weights on certain markers leading to increased variability, particularly in the knee and hip. These findings emphasize the importance of carefully selecting marker weights to achieve consistent outcomes and pave the way for future research to refine motion analysis techniques further.

Acknowledgments

This study was financially supported by Indonesia Endowment Fund for Education (LPDP). The authors extend their heartfelt gratitude for this valuable support.

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