COMPARISON OF THE STATICALLY EQUIVALENT SERIAL CHAIN CENTER OF MASS ESTIMATION METHOD TO OPENSIM'S RESIDUAL REDUCTION ALGORITHM

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ABSTRACT

COMPARISON OF THE STATICALLY EQUIVALENT SERIAL CHAIN CENTER OF MASS ESTIMATION METHOD TO OPENSIM'S RESIDUAL REDUCTION ALGORITHM

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Being able to determine a person's center of mass (COM) location is very important and useful to many studies, but not easily calculated. COM is used in a variety of studies, especially those dealing with balance, as COM must be over the center of pressure (COP) for something to maintain balance in a static position. An open-source software called OpenSim has its own COM estimation built into its Residual Reduction Algorithm (RRA) and is widely used in the field of biomechanics. This study seeks to compare the accuracy of this estimation to a recently developed COM estimation method called the Statically Equivalent Serial Chain (SESC) estimation. This study uses data collected via motion capture and force plates to further validate the SESC method as well as compare its accuracy to that of the currently implemented RRA through motion capture and data processing in OpenSim and MATLAB. Motion capture data provided an accurate representation of subject kinematics used in both COM estimations, and force plate COP as the metric for comparison in the horizontal directions. For data collection, 1 PVC humanoid and 16 subjects between the ages of 18 and 50, stood in 40 static poses. The poses were initially processed through the motion capture software, Vicon Nexus, and then inverse kinematics, dynamics, and RRA in OpenSim. Finally, the SESC COM

estimation was determined using this processed data through a custom MATLAB script, and the magnitude of the error in the horizontal plane of all subjects' poses was analyzed.

The SESC estimation proved to be significantly better than the OpenSim estimation using RRA through analysis of variance (ANOVA) testing, with an average error of 7.82 mm for SESC and 10.69 mm for RRA ($p<0.0001$, $P=0.99$). Additionally, the SESC error maintained its accuracy within this new experimental study, being below the maximum error of previous COM estimation studies. This study differs from other studies because of its more developed breakdown of the human body into vectors for SESC, allowing for more free moving joints, as well as a much larger set of collection data for analysis. This significant difference has proven that SESC is a worthwhile COM estimation to be used in biomechanical studies, and could viably be implement into a software like OpenSim as an improvement to its COM estimation.

Dedicated to my parents who have believed in and support me in all my pursuits, and to Wayne for always watching my back.

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LIST OF ABBREVIATIONS AND NOTATIONS

ANOVA	Analysis of Variance
BOS	Base of Support
COM	Center of Mass
COP	Center of Pressure
DIMLab	Design of Innovative Machines Lab
ID	Inverse Dynamics
IK	Inverse Kinematics
IQR	Interquartile Range
SESC	Statically Equivalent Serial Chain
RRA	Residual Reduction Algorithm

INTRODUCTION

Overview of Center of Mass

The center of mass (COM) of an object is the average position of a distribution of mass in space. Knowing the location of the COM of an object is pivotal when performing a wide variety of calculations and determinations regarding how that object may move or react to surroundings. When dealing with humans, determining exact COM is not easily attained, as it is unrealistic to go inside of a person to verify their mass proportions. Thus, various methods have been developed to estimate a person's COM, as it is pivotal to many studies in the biomedical sciences. Prediction of COM has been studied in a variety of fields, with primary efforts in Robotics and Biomedical Engineering, specifically Biomechanics. As understood from general physics and more explicitly elaborated in The Condition for Dynamic Stability by A.L. Hof, et al., the “condition for standing stability in static situations is that the vertical projection of the COM should be within the base of support (BOS)”[1]. A study by X. Xinjilefu, et. al., provides insight into how this knowledge of COM can be applied, and the importance of estimating it[2]. The authors developed their own COM estimation methods that was implemented into a robot to prevent the robot from falling during fall testing[2]. As you can imagine, being able to understand where the COM is in a robot becomes very essential to its functionality. While humans utilize very different mechanics in their motion, the same principles apply.

The importance of knowing the COM for stability in humans has been supported by many studies[2–4], but the method for determining it has varied depending on the study.

Generally, people have come up with their own methods for estimating COM that work specifically for their study, but in the field of biomechanics many studies primarily use the built-in estimation of COM in commercially available software packages. One such software is OpenSim[5–7]. OpenSim is a free, open-source software that allows for "modeling, simulating, controlling, and analyzing the neuromusculoskeletal system"[7], which has put it at the forefront of musculoskeletal biomechanics studies. Generally, OpenSim's tools are used to analyze human motion by creating a model of the human body containing bones and joints and moving the model to replicate the motion of a human. Typically, the human body model is created from a generic model that represents a 75 kg, 1.7 m male with mass and inertia properties obtained from generic anthropometric data[8]. The generic model is typically scaled to match an individual's total body mass, but the distribution of mass within the body is maintained from the generic model. For individuals with varying body dimensions and mass distribution, use of the generic model will cause error in OpenSim's COM estimation method. After model scaling and preliminary kinematic analysis, OpenSim's built-in COM estimation is often required before many of its other features can be utilized. This means that any error in its COM estimation might reflect in the error of the resulting findings. The more accurately the COM is estimated, the more accurately the findings from following studies could be reported.

Residual Reduction Algorithm (RRA)

OpenSim has a multitude of available analysis tools, many of which operate in sequence, building off one another. OpenSim's built-in COM estimation occurs within the "Reduce Residuals Tool" and uses what is known as its Residual Reduction Algorithm (RRA). As errors develop in experimental data collection, modeling, and simulating, the forces applied to the skeleton segments to move it and the ground reaction forces begin to not satisfy Newton's Second Law. RRA is mean to account for this by removing the muscles from the model and replacing them with torque actuators applied at each joint to develop kinematics and mass distributions, within only the skeleton, that are more consistent with the ground reaction forces and the skeleton[7]. RRA computes the actuator torques required to move the skeleton based on the previous kinematics frame by frame, starting at the first second of captured data. After it has done this for all frames and simulated the full trial, it calculates new residual forces to be applied to the pelvis to account for dynamic inconsistencies with Newton's Second Law. Following this, RRA makes adjustments to the model's COM to account for inaccurate mass distributions, resulting in an adjusted COM that is of interest in this study. Although the adjusted COM is obtained to improve dynamic consistency between the data and model, the mass distribution in the model is not specific to the individual and therefore, may lead to error in COM location.

Statically Equivalent Serial Chain (SESC)

There is another method of estimating a human's COM called the Statically Equivalent Serial Chain (SESC) estimation, that has been recently developed by Sebastien Cotton, Andrew Murray, and Philippe Fraisse and has promise to be a consistently accurate estimation of COM in humans[9]. In developing this method, S. Cotton, et. al., determined that you can model human segments that are separated by joints into vectors that are linked at their end effector positions in a branched chain. By then modeling the joints as revolute or spherical, many variables become constants and allow the COM to become a simplified formula solved utilizing matrix math. Its accuracy is based on the requirement that all joints can be modeled as revolute or spherical, and that joint data is available, which is almost always available in OpenSim studies. The advantage of this method when compared to other COM estimation methods, proved to be in its ability to quickly determine COM without force plate data in real time. This is because SESC requires calibration with COP data from a force plate, which yields results very close to other COM estimations, but once calibrated, it can be quickly determined using the calibrated equation and no additional force plate data[9]. Another key advantage is that its COM estimation is not influenced by the generalized mass distributions that are used in many studies and programs (such as RRA in OpenSim), but rather has an accurate COM estimation specific to the subject due to its necessary calibration step.

The advantages of the SESC COM estimation method make it a promising method to be applied and utilized more widespread, but not everyone uses the same experimental setup that S. Cotton, et. al. used for their validation. In their study they used the COP of various subjects standing on a single force plate. This study sought to determine and validate how this estimation could be applied to more common biomedical motion capture setups with multiple force plates, specifically compared to OpenSim.

Metric for Comparing COM Accuracy

In a static pose, a person's COM position in the horizontal plane lines directly above their center of pressure (COP). Following this logic, a person's COP can accurately define their COM in the two horizontal plane directions in a static pose. Since COP is easily captured using force plates during a motion capture study (if force plates are available), it becomes a definitive comparison to determine the accuracy of a COM estimation for static poses.

The focus of this study consisted of performing a motion capture study collecting kinematic and COP data with both a PVC humanoid model as well as human subjects. We implemented both SESC and RRA side by side to determine if the SESC model can be used to improve OpenSim's COM estimate. This determination would be done by comparing the horizontal components of both methods with the COP as the 'correct' value, and analyzing the resulting error. Based upon previous results, we hypothesize that the SESC estimation model will not only retain its accuracy and reliability seen in previous research, but also provide a more accurate estimation for COM than the RRA for all subjects in the static condition. By applying these processes for data collection, processing, and COM estimating utilizing both SESC and RRA in OpenSim on human subjects, this study sought to open the possibility of SESC for widespread use in the biomedical field and address the concerns in the error of the currently used RRA method.

METHODS

Subjects

For the PVC humanoid model, a custom model built through previous research done by the University of Dayton's Design of Innovative Machines Lab (DIMLab) was used.

Figure 1: The PVC humanoid model created by University of Dayton's DIMLab used in this study.

For the human collection, 16 healthy people between the age of 18 and 50 volunteered to be participants in this study. Participants were only excluded if they reported that that could not balance in static positions of their choice for a few seconds at a time. No participants reported this. Subject 01 was excluded from the results as limited data were available for this subject. Data presented in this study starts with subject 02. For the 15 subjects (10 male, 6 female) included in the results, the average (standard deviation) height, weight, and age were 173.4 (9.0) cm, 74.3 (13.4) kg, 26.25 (6.12) yrs, respectively. Subject demographics can be seen in Table 1.

Table 1: Subject Demographics

Subject #	Height (cm)	Weight (kg)	Sex (M/F)	Age (yrs)
1	190.5	83.9	M	22
2	170.2	73.0	M	22
3	152.4	72.6	F	37
4	175.3	102.1	M	28
5	177.8	68.0	F	23
6	178.0	104.0	M	26
7	162.6	68.6	F	36
8	177.8	67.2	M	27
9	167.6	61.6	F	22
10	170.2	61.5	F	22
11	165.1	64.9	M	25
12	180.3	77.3	M	41
13	180.3	69.2	M	21
14	180.3	83.0	M	26
15	180.3	79.9	M	21
16	165.1	53.5	F	21

All data were collected in the Motion Analysis Lab in Fitz Hall on the University of Dayton’s campus. Before participating, participants performed and passed a selfassessment for COVID-19 symptoms, provided written consent for both the study and the COVID-19 guidelines in the laboratory, of which was approved by the University of Dayton Institutional Review Board.

Protocol

The PVC model and participants were fit with a custom set of retroreflective markers to be seen by the cameras in the motion capture system. This set of markers included all body appendages aside from the head and was created through a combination of the premade Vicon (Oxford Metrics, UK) PlugInGait FullBody Ai model[10], general segment tracking guidelines from C-Motion[11], and motion tracking requirements for the SESC method. Any reflective surfaces on the subject's clothing were covered, and any accessories that may conflict with motion tracking were removed. Specific marker convention can be seen in Figure 2.

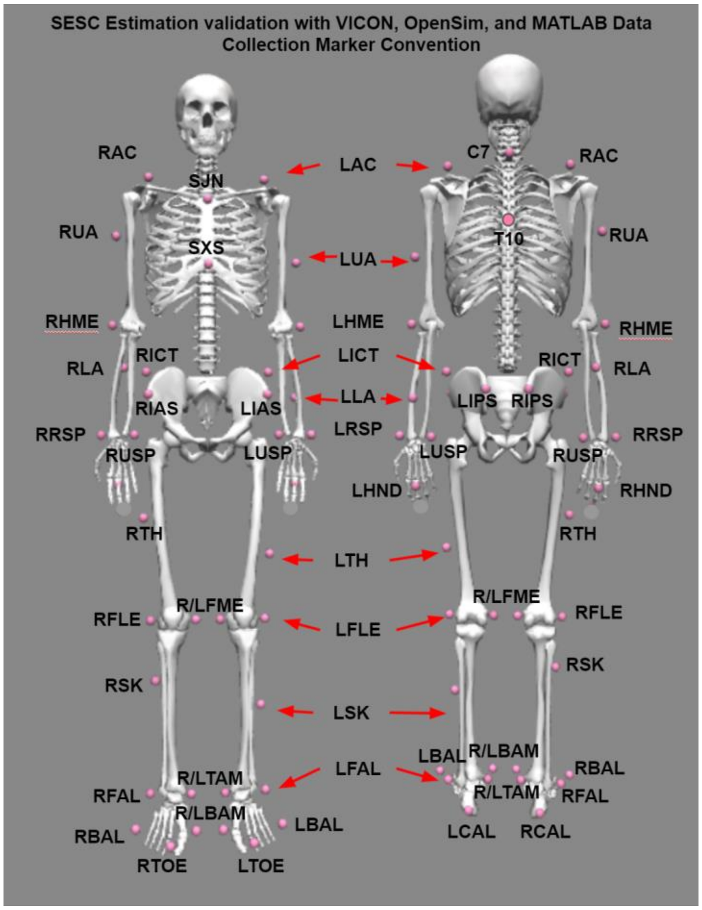

Figure 2: The 45-marker layout used for motion capture data collection in this study.

An 8 camera Vicon (Oxford Metrics, UK) motion capture system was used to capture marker positions at 150 Hz within the motion capture volume, where the participants would stand on 2, in-ground Bertec (Columbus OH, USA) force plates, that both collected ground reaction force data at 1500 Hz.

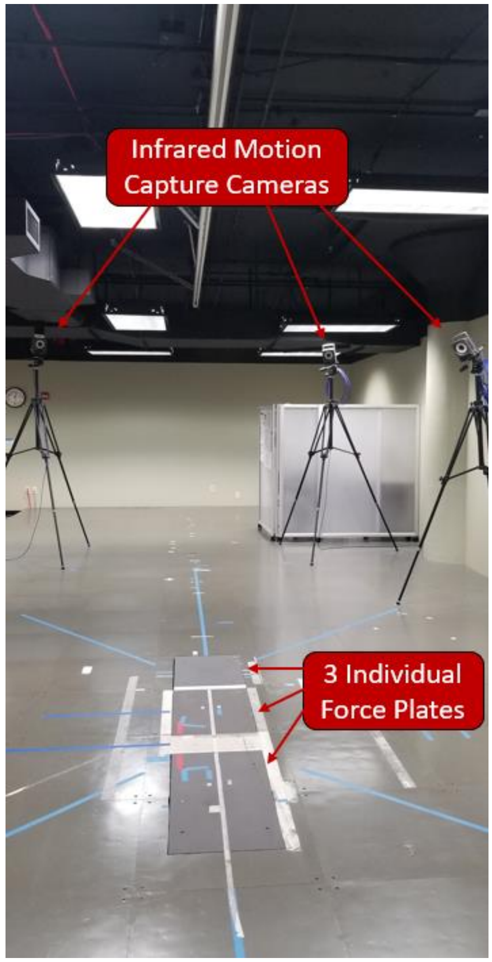

Figure 3: Motion capture volume used for data collection in this study. Located in the University of Dayton's Motion Analysis Lab

The Vicon cameras send infrared light out which is reflected by the markers, allowing them to be tracked in 3D space by the cameras, and further, recorded by the Vicon software: Vicon Nexus.

The data collection consisted of taking 1-second, static poses. 35 poses were collected for the PVC humanoid model, and 40 were collected for the human subjects. These numbers are based on SESC calibration requirements and will be discussed further. For each pose, the PVC humanoid was placed and the subjects were instructed to stand with each foot on its own, specific, force plate for all of the data collection. The foot position could be changed between poses, or even removed from the force plate, so long as no other forces were introduced to the 2 force plates used besides the corresponding feet. All poses were determined by the subject themselves during the data collection, based on their comfort level and imagination, resulting in 40 unique poses for each subject. If the system could not properly track a pose, the subject was not static, or other possible capture errors occurred, the pose was simply re-taken, or extra poses were taken at the end and used as replacements.

Data Processing

The first step in processing the data was to verify and label the marker positions captured in the Vicon Nexus software. This is done by applying a pre-built skeleton to the captured marker set, running the built-in labelling pipelines, and then fixing any mislabeled or unlabeled markers. Once it has been verified that there are sufficient number of well tracked and fully labeled trials, the data were exported and converted to be used in OpenSim[5,6]. This is done through a conversion code in MATLAB that changes the marker data files to .trc files, and the ground reaction force data to .mot files, both of which formats are used in OpenSim.

In OpenSim, the data were then run through a series of steps starting with scaling the model based upon the first static trial where all markers appear. This step adjusts a generic, full-body model[12,13]to match the size and shape of your specific subject more closely, as well as adjust marker positions for that specific subject. For the PVC humanoid, a custom OpenSim model had to be created with segments and joints based on various subassemblies from the corresponding SOLIDWORKS (Dassault Systèmes

SOLIDWORKS Corp, Waltham, Massachusetts, USA) file that was created by the research group that developed the PVC humanoid. This meant that for the PVC model the segment mass properties and sizes were fully accurate and did not need to be adjusted with the scale tool in OpenSim, only the body orientations and marker positions.

Following the scale tool, the inverse kinematics (IK) tool was used to create motion files in OpenSim that positions the model to match each of the poses held by the participant over the 1 second trial period by moving the segments and joints to minimize marker error.

Next, was the inverse dynamics (ID) tool which determines the net forces and torques at each joint to produce the motion. Predominantly ID was done because it required the creation of an external loads file which applies the ground reaction forces from each force plate to the correct locations on the model (in the case of this study, to the proper left or right foot segment), and running ID helps validate the ground reaction forces were applied correctly.

After ID, the RRA tool was used, which requires the model file, kinematics, and external loads files, as well as a tasks file and actuators file. The tasks file is used to further weight which joint angles should be tracked more closely, and the actuator file is a file containing parameters for ideal joint actuators that actuate the model in RRA. Because of this, custom task and actuator files were created for the PVC humanoid and each human subject. The results of the RRA tool includes many files but primarily a states.sto file, controls.xml file, as well as adjusted kinematics that contains information on their newly adjusted COM for the model for the specified motion. This adjusted COM is applied to a modified model that normally would be used for further OpenSim tasks in a study that requires it, and is also the COM value that will represent OpenSim in the comparison at the end of data processing. Also, the states and controls output files contained more elaborated information about the motion on the model, allowing for the analysis tool to be used.

The analysis tool was used to provide node locations for the various joints of the body. These joints differed between the PVC humanoid and the human subjects but the process was the same. An example of these joints includes the knee joint location, hip joints, shoulder joints, etc. The node locations for each pose were then generated and read into MATLAB scripts that created vectors based on the node locations and performed the required calculations to estimate the COM of the subject based on the SESC method. The SESC method requires at least as many poses as node locations to calibrate, with more poses used being more and more effective, falling off after about 1.5x the number of nodes. On the PVC humanoid model there were 14 node locations, meaning 21 poses were used for calibration, and 14 poses for testing, totaling the 35 poses mentioned previously. For human subjects there were 16 node locations, meaning 24 poses were used for calibration, and 10-16 poses were tested per data collection. This was done 3-4 times per subjects with changing calibration poses, so that every pose could be used as a testing pose at some point, for a more robust comparison. Any poses used as testing poses multiple times had their error averaged.

The difference between the COP and the resulting SESC or RRA COM estimation was recorded for each pose. The error for all poses were averaged per method, per subject. For the PVC humanoid the SESC method was calculated using 5 different sets of calibration poses, to further understand if the poses used for calibration had an effect on

COM estimation accuracy. These sets of poses used for calibration were first numbered poses, last numbered poses, predominantly even numbered poses, predominantly odd numbered poses, and completely random using a random number generator. For the human subjects, some data was deemed unusable throughout the data processing for a variety of reasons, including inconsistent force plate reading due to human subject error, poor marker tracking, high inverse kinematic error, etc. Of the usable poses, 24 were chosen at random for calibration. The remaining poses were used as test poses for COM comparison. The COM values produced in the horizontal axes' directions by the COP, the SESC method in the custom MATLAB script, and OpenSim's RRA, were grouped for direct results comparison and analysis.

Statistical Analysis

No statistical analysis was done for the results of the testing on the PVC humanoid model, as it was used simply to validate and further improve the experimental methods before human subject testing.

For the human subjects, Method Error was calculated as the magnitude of the X and Z components of error (difference) between the model (RRA or SESC) center of mass and the force plate COP data. Commercial statistical software (NCSS, version 2020) was used for all statistical calculations. A repeated measures analysis of variance (ANOVA) was utilized with significance set at $p<0.05$. All data was tied to the particular subject code and subject ($n=15$) was included in the ANOVA. A within factor of Method (levels of OpenSim and SESC) was analyzed. Data between OpenSim and SESC was balanced, and each subject had between 32 to 40 poses for comparison. A total of 559 data points were included for each method.

RESULTS

PVC Humanoid

For the PVC Humanoid model, the COM error of both SESC and RRA for all testing poses was averaged for each SESC calibration method, and the comparison can be seen in Figure 4 below.

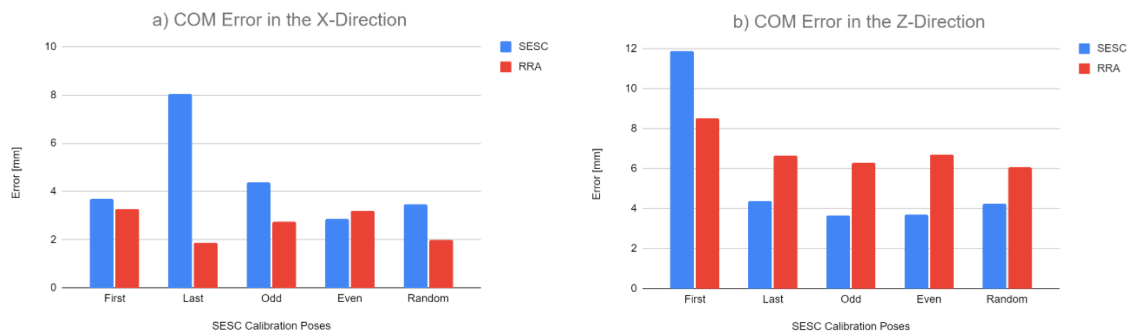

Figure 4: COM Error of both the RRA and SESC estimation in the a) x and b) z direction for the PVC humanoid model

The RRA estimation was better for all but one calibration method in the x-direction, and the SESC method was better for all but one calibration method in the z-direction. The average (standard deviation) error across all testing trials were calculated and were 4.49 (2.06) mm (x-direction) and 5.58 (3.54) mm (z-direction) for the SESC method and 2.62 (0.66) mm (x-direction) and 6.85 (0.98) mm (z-direction) for the RRA method. This resulted in RRA having less overall error than SESC by 1.87 mm in the x-direction and SESC having less overall error than RRA by 1.27 mm in the z-direction.

Human Subjects

The average error across all poses was categorized by the individual subjects and by the COM estimation method. For the SESC estimation method, the average (standard deviation) error was 4.67 (4.34) mm in the x direction, and 5.25 (5.43) mm in the z direction. The average error across all poses for the RRA estimation method was 7.55 (8.54) mm in the x direction and 6.01 (7.03) mm in the z direction. Due to the variety of subject orientation during data collection, the x and z directions do not have any correlation to specific biomechanical directions or poses, so the magnitude of error was determined and further investigated instead. The resultant magnitude of the error between the x and z direction was 7.82 (6.05) mm for SESC and 10.69 (10.07) mm for RRA. From the ANOVA results, the factor of Method was significant ($p<0.0001$, $P=0.99$). Method error was significantly lower for the SESC approach versus the RRA approach.

Subject specific results (Figure 5) show the boxplot of Error values grouped by method with OpenSim in red and SESC in blue. The box plot shows a box representing ±1.5X the Inter-Quartile Range (IQR) and whiskers representing ±3.0X the IQR. Outliers are omitted. Median is shown as a line across the box. Mean is shown with a filled circle.

Generally, the SESC method can be seen to have lower error values than the RRA method aside from certain specific subjects, supporting its statistical significance, as well as having visibly smaller IQRs than the RRA method.

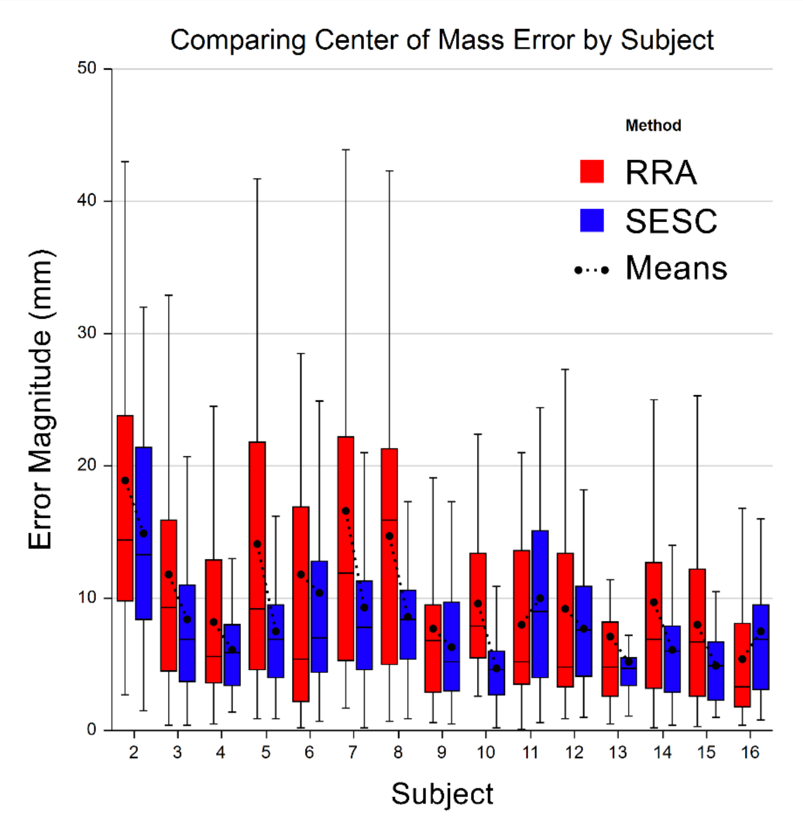

Figure 5: Boxplot of error magnitude values per human subject, grouped by the 2 methods compared: RRA method from OpenSim RRA (red) and SESC (blue)

The SESC and RRA estimation values in the y direction (vertical) were recorded and compared to investigate differences between the methods. As the COM location in the y direction cannot be verified by a metric such as COP, this metric has no "true" value. Due to their increasing reliability on their specific corresponding pose as well as no "true" value to compare against, no analysis was done on these values, and the y direction COM location can be seen in Appendix B.

DISCUSSION

The focus of this study was to perform a motion capture study collecting kinematic and COP data with both a PVC humanoid model as well as human subjects. We implemented two methods for COM estimation, SESC and OpenSim's RRA side by side to determine if the SESC model can be used to improve OpenSim's center of mass estimate. The error in the SESC COM estimation was significantly lower than the RRA estimation and therefore, SESC may be a viable method to implement into a software like OpenSim in the future.

The RRA and SESC estimation were similarly accurate for COM estimation of the PVC humanoid. The very low error from RRA is logical as the OpenSim model for the PVC humanoid incorporated exact mass distributions, and no mass distribution assumptions were made by OpenSim during its COM estimation process. Additionally, for the PVC humanoid, the SESC estimation has proven that it can retain its accuracy through the data collection and processing in OpenSim, with errors averaging under 5 mm. The high accuracy of both RRA and SESC validated the experimental methods for the application of SESC and warranted the continuation of the study to human subjects. Different results were anticipated with human subjects due to the mass distribution assumptions made by the human modeling process.

The ANOVA results showed that the SESC estimation method was significantly better than the RRA method in this study with an overall average error between estimated COM location and known COP location of 8.97 mm across all subjects and poses. The tighter IQRs in the errors show more consistency in the SESC method for most subjects.

SESC's smaller errors and variability is likely due to the strengths of the calibrated SESC method in matching specific subjects or more extreme poses. Additionally, it can be seen that some subjects (for example, subjects 2 and 11) have larger errors than the majority of subjects for both SESC and RRA. For SESC, the large error is probably because of a less than optimal pose being used in the calibration process for that specific subject and could be improved if different poses were used to calibrate SESC. For RRA, the larger error could arise because of poor mass adjustments for that subject, whether it be because the subject has more uncommon mass distributions or another unique difference in body dimensions that would result in worse optimization and error reduction during RRA.

The SESC method alone in this study produced an overall average error of 7.82 mm, which lies below the maximum error of 12 mm but slightly above the average error of 5 mm from the original developmental SESC study[9]. This error from previous study, however, was only in one direction, the x direction, meaning that factoring in the additional z direction, may put the values from this study below the values determined accurate for SESC previously. The resulting error from this study is also lower than the results of another study by González, A., et al, that similarly utilized the SESC estimation and resulted in an average error of 12.8 ± 9.1 mm[14]. This is to say that SESC has retained its accuracy in this biomechanical study setting, using OpenSim for primary data processing and MATLAB for application of SESC.

This study differs from the previous study validating the SESC method, and other studies that use it because of its methods, context, and data quantity used to support its validation. In the original study[9], 1 subject with 19 poses was used, and the error was only calculated in the x direction for 5 poses. The current study has taken a more developed stab at applying the SESC method by breaking the human body down in a more complex model with added vectors, as well as including additional poses. By including 15 subjects with 40 poses of COM comparison data each, the current study has substantially bolstered the experimental support for this method as a viable method in a biomechanical field of study. Additionally, the current study also included a direction comparison with a currently used COM estimation in the software OpenSim. This study has successfully proven the accuracy of the SESC method to be better than the current RRA method, and viable for use in the same or similar biomechanical data collection and software in future studies.

Limitations

One limitation of this study is that the subject pool used in the human data collection contained relatively young, healthy adults, covering a less extreme demographic. This may have affected our results by creating more simplified human models for the tested COM estimation methods. Future studies should seek to use a wider demographic when collecting data on humans, such as subjects with known non-uniform mass distributions, to further investigate how well these COM estimations would perform. Another limitation of this study was that the head appendage was not included in either COM estimation method and could have had an influence on the actual COM position, possibly skewing the errors determined. While this may have made the estimations slightly worse, it should have affected both estimation methods similarly, meaning that the statistical comparison of the two methods would remain valid.

CONCLUSION

In conclusion, accurately estimating a person's COM is very important in biomechanics, and the SESC method has proven to retain its accuracy as an estimation method, even when applied to motion capture data that has undergone an array of biomechanical processes in OpenSim. Additionally, it still holds its additional advantages as a COM estimation method that can be preferrable to some biomechanics studies and can conclusively be stated to be better than OpenSim's current COM estimation using RRA. This study thoroughly supports future use of SESC, specifically in biomechanical settings, and further validates it as an accurate COM estimation method. Therefore, the SESC method is viable for implementation into a biomechanical software like OpenSim. Recommendations for future studies would include encouraging subjects to use more extreme static poses to test the limits of the SESC estimation, as the truly extreme poses used in this study were not very common. Additionally, due to the large set of poses that was processed for this study, it became difficult to fine tune certain OpenSim processes, such as RRA, to specific individual trials. Furthermore, SESC estimation in this study was done using 1.5x the minimum required calibration poses for a good calibration, but the influence of using more or less calibration poses was not investigated in detail. Further studies could investigate the results of a similar study, focused on fine tuning the COM estimations used on a smaller data set.

This study has successfully shown the tremendous accuracy, alongside other benefits, of the SESC COM estimation method, specifically over OpenSim's estimation using RRA, as well as the feasibility of implementing it into a motion capture software like OpenSim.

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APPENDIX A

Marker Convention Descriptions*

UPPER ARMS
RAC/LAC = Acromial (Bony Landmark on Shoulder)
RUA/LUA = Upper Arm
RHLE/LHLE = Humoral Lateral Epicondyle (bony landmark on outside elbow)
RLA/LLA = Lower Arm
RRSP/LRSP = Radius Styloid Process (outside bony wrist landmark)
RUSP/LUSP = Ulna Styloid Process (inside bony wrist landmark, usually large protrusion)
RHND/LHND = Hand

TORSO ANTERIOR
SJN = Sternum Jugular Notch ("u-shape" at the top front of rib cage)
SXS = Sternum Xiphisternal Joint ("u-shape" at the bottom front of rib cage)
LICT/RICT = Illiac Crest Tuberble (top of the bony hip)
LIAS/RIAS = Ilium Anterior Superior (front protruding bony landmark on hip)
T10 = The Tenth Thoracic Vertebra

TORSO POSTERIOR
C7 = Cervical Vertebrae 7
RISP/LIPS = Ilium Posterior Superior (bottom of spine, about an inch on either side)

LOWER BODY
RTH/LTH = Thigh
RFLE/LFLE = Femoral Lateral Epicondyle (outside knee joint: feel for the joint by slowly raising and lower the leg)
RFME/LFME = Femoral Medial Epicondyle (inside knee joint: feel for the joint by slowly raising and lower the leg)
RSK/LSK = Shank (lower leg)
RFAL/LFAL = Fibula Apex of Lateral Malleolus (outside bony landmark of ankle)
RTAM/LTAM = Tibia Apex of Medial Malleolus (inside bony landmark of ankle)
RTOE/LTOE = Tip of toe (line up with the CAL marker in both X and Y directions)
RCAL/LCAL = Calcaneus (Heel, line up with the CAL marker in both X and Y directions)
RBAL/LBAL = Lateral ball of foot
RBAM/LBAM = Medial ball of foot

44 MARKERS TOTAL
*"Outside" and "inside" refer to the lateral and medial directions, respectively, and reference the body segments and joins specifically in Standard Anatomical Position

APPENDIX B

Subject Test Poses and Y Direction (Vertical) COM Values

Table 2: Test Pose Numbers Used for Each Subject

Subject #	Testing Poses
2	2 6 7 8 9 11 15 16 18 24 28 30 33 34 36
3	3 5 6 9 13 14 17 20 21 24 25 26 32 34 37
4	3 4 8 15 16 17 21 25 27 28 31 32 33 34 35 36
5	3 7 11 13 14 16 20 21 23 29 31 33 36 38 40
6	1 8 16 20 23 26 28 30 31 36 39 40
7	8 14 18 22 25 27 30 34 37
8	9 12 13 16 19 22 28 30 35 39 40
9	1 6 10 14 16 17 19 21 23 28 30 39 40
10	2 7 8 13 14 15 20 21 23 26 28 29 34 39
11	4 5 7 8 9 14 24 27 33 34 38
12	1 4 8 10 12 14 22 25 31 38 39
13	1 6 8 11 15 20 28 29 30 31 32 33 35 38 39 40
14	1 7 8 11 15 18 19 20 21 26 30 32 34 37 38
15	1 5 8 12 14 17 27 30 35 40
16	2 5 6 7 10 12 13 14 15 16 23 30 32 34 36 37

Table 3: SESC and RRA Estimation Y Direction Values

S02		S03		S04		S05		S06	
SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y
0.94571	0.95413	0.90217	0.90544	0.98792	0.956	0.97426	0.98299	0.98845	0.96322
0.81268	0.82662	0.78314	0.78611	0.98495	0.95437	0.89392	0.91627	0.94124	0.929
0.772	0.78053	0.76689	0.77604	1.00496	0.96834	0.95741	0.96769	0.99447	0.98082
0.84554	0.85449	0.82645	0.83445	0.98051	0.94887	0.94438	0.96568	0.99045	0.97046
0.92343	0.92886	0.81863	0.8328	0.97883	0.94896	0.91211	0.96022	0.98378	0.95659
0.94348	0.94829	0.81881	0.82286	0.96527	0.93667	0.98263	0.99426	0.97509	0.95158
0.91294	0.93405	0.77924	0.78886	0.88676	0.86567	0.85464	0.87575	0.98256	0.95731
0.94465	0.9675	0.81343	0.82836	1.0018	0.97301	0.82993	0.85979	1.00778	0.99805
0.88999	0.89301	0.86947	0.87502	1.01363	0.9881	0.87242	0.89419	0.99861	0.97091
1.00033	1.01538	0.77781	0.79313	1.00098	0.96584	0.8339	0.86008	0.99388	0.97714
0.6309	0.65648	0.87908	0.88574	1.00435	0.97165	0.91614	0.94269	0.99445	0.97758
0.91051	0.87026	0.81029	0.81146	1.0283	1.00049	0.91933	0.95622	0.97337	0.95264
0.95084	0.95488	0.79562	0.83492	1.00164	0.96542	0.91022	0.93032		
0.89862	0.87818	0.93085	0.94944	0.98717	0.95183	0.86521	0.88917		
0.88098	0.85017	0.93702	0.93406	1.01601	0.98315	1.02089	1.06176		

S07		S08		S09		S10		S11	
SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y
0.75858	0.76285	0.98482	0.9678	0.9298	0.9535	0.69281	0.72111	0.91843	0.91718
0.91878	0.92454	1.00568	1.00482	0.92485	0.95607	0.80878	0.83022	0.88705	0.89186
0.73987	0.74293	0.90433	0.89426	0.9323	0.96163	0.7776	0.79208	0.89655	0.90121
0.74208	0.76534	1.02369	1.01494	0.84457	0.87589	0.95182	0.97218	0.90269	0.90629
0.8084	0.79493	1.01792	1.01723	0.95566	0.98373	0.751	0.78059	0.86336	0.86761
0.61353	0.60636	0.92069	0.89889	1.00428	1.03694	0.78796	0.81007	0.80982	0.82014
0.88736	0.88629	0.81606	0.80579	0.79158	0.81821	0.8306	0.84798	0.91964	0.92941
0.95632	0.97989	1.04321	1.03187	0.93018	0.95317	0.72543	0.75751	0.90881	0.90697
0.8098	0.82283	1.02113	1.01984	0.85644	0.88791	0.87964	0.90584	0.89064	0.8905
		0.84252	0.83714	0.90744	0.93719	0.91544	0.92911	0.92223	0.91771
		0.85646	0.85211	0.91619	0.94561	0.85656	0.87151	0.90996	0.91888
				0.88733	0.91147	0.82605	0.85432		
				0.88382	0.91037	0.83299	0.84486		
						0.83033	0.84944		

S12		S13		S14		S15		S16	
SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y	SESC Y	OSim Y
0.98039	0.93603	0.98858	0.98352	0.99389	1.02886	1.12502	0.96653	0.93412	0.91547
0.93456	0.9131	1.01864	1.01321	0.99835	1.03061	1.07786	1.01467	0.94687	0.93778
0.99205	0.96938	0.95899	0.96183	0.97968	1.0126	1.12553	1.00239	0.94736	0.93864
0.9422	0.90898	0.88773	0.88617	0.88345	0.90844	1.0898	0.97603	0.94791	0.93566
0.96389	0.9383	0.99792	0.98442	1.02015	1.0498	1.12853	0.99276	0.94518	0.9314
0.93769	0.90184	0.92859	0.92069	1.01909	1.05176	1.12014	0.99241	0.93944	0.91999
0.97993	0.95378	0.96626	0.94494	1.0431	1.0727	1.10026	0.98962	0.93752	0.91466
0.9827	0.95027	0.96844	0.94599	1.06159	1.10083	1.09602	0.96686	0.93778	0.91876
0.78621	0.75906	0.99463	0.98375	0.98651	1.01815	1.09703	0.9636	0.9148	0.89445
0.98887	0.94105	0.99738	0.9866	0.9551	0.98674	1.05343	0.94851	0.91979	0.90472
0.97723	0.9418	1.00454	0.99932	0.81336	0.82631			0.97037	0.97066
		0.95468	0.94865	0.9654	0.99855			0.92639	0.91531
		0.96939	0.96649	0.99078	1.0265			0.95995	0.94602
		1.01678	1.00259	0.97911	1.01228			0.94269	0.934
		1.01536	1.002	1.0011	1.03602			0.93693	0.92524
		1.02892	1.01677					0.92824	0.91227