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THE INFLUENCE OPTICAL MOTION CAPTURE SAMPLING FREQUENCY HAS ON DATA COLLECTION OF COMMON TASK KINEMATIC DATA

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by

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A Research Paper
Submitted in Partial Fulfillment of the Requirements for the
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RESEARCH PAPER APPROVAL

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Approved by:

Dr. Sean Quisenberry

Graduate School
Southern Illinois University Carbondale
July 6, 2023

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CHAPTER 1

INTRODUCTION

Since the increased availability of optical motion capture technology in the early 2000s, typical data acquisition frequencies for assessing ankle, knee, and hip joint kinematics have ranged from 200-250 Hz (Drazan et al., 2021; Hemmerich, et al., 2006). However, studies investigating the kinematics of the Oxford and Rizzoli multi-segment foot models have commonly utilized frequencies at or below 200 Hz, regardless of movement (Deschamps et al., 2019; Shono et al., 2022), which falls significantly short of the International Society of Biomechanics' recommended frequency of 500 Hz for skin marker-based multi-segment foot kinematics (Leardini et al., 2021). Consequently, it is crucial to understand the impact of optical motion capture sampling frequency on experimental outcomes. This understanding can potentially enhance our comprehension of human movement through the utilization of optical motion capture technology.

The utilization of this method enables precise and accurate recording of motion, achieving submillimeter precision and capturing motion at high speeds of several hundred samples per second (or Hertz, Hz). Topley et al. (2020) conducted an assessment of the accuracy of various optical motion capture technologies. Their findings indicated that all systems, regardless of generation, were capable of accurately determining the distance between retroreflective markers attached to a rod and/or a plate, with a maximum error of less than 1.03 mm. Furthermore, they observed that the accuracy of measurements increased with higher camera image resolutions, measured in megapixels (MP), reaching an accuracy of ±0.058 mm for a 16 MP camera. Despite these significant advancements, it is important to recognize that a crucial aspect of motion capture technology that remains unaddressed in the existing literature is the determination of an applied optimal sampling frequency for data collection. The lack in knowledge of this aspect of motion capture technology hinders our ability to accurately perform studies and draw reliable findings.

In the context of sampling frequency, it is critical to note that the optimal rate is not solely determined by the speed of the motion, but also by the spatial proximity of the markers. The minimum frame rate is proportional to the ratio between the maximum speed of the motion and the minimum spacing between markers, necessitating a higher frame rate for successful motion tracking when markers are closely spaced (Song & Godøy, 2016).

Lower extremity movements are crucial for daily physical function, fall injury prevention, and sport participation. Furthermore, it is considered a minimally invasive means of tracking human movement and allowing the human body to move through a wide range of movements. A study assessing the prevalence of lower extremity injuries in college over a two-year period NCAA athletic program found that of all musculoskeletal injuries, foot, and ankle made up nearly 27% (Hunt et al., 2016). Another important aspect of lower extremity function is balance. Maintaining mobility and avoiding falls is heavily dependent on balance which relies on lower extremity movements. Weakness in lower extremity muscles puts older adults at risk for balance loss and fall injuries (Muehlbauer, et al., 2015)

Furthermore, a better understanding of lower extremity movements can aid in injury prevention and recovery. Therefore determining optimal sampling frequencies for these movements may enhance the accuracy and reliability of motion capture technology.

Therefore, the aim of this study is to investigate the influence of sampling frequency on the kinematics of a multi-segment foot model during walking and running. This will be achieved by utilizing two synchronized motion capture systems, with one system sampling at twice the frequency of the other. By comparing the kinematic data collected at different sampling frequencies, we can gain insights into the effects of sampling frequency on the accuracy and precision of the multi-segment foot model analysis.

CHAPTER 2

METHODOLOGY

Subjects

The study recruited 15 adult participants between the ages of 18 and 32. Before the testing, the participants gave informed consent that was approved by the institution. Those who were unable to perform common activities of daily living for at least 60 continuous minutes or had participated in intense training or competitive sports within the past 24 hours were excluded from the study.

Instrumentation

Two synchronized six-camera motion capture systems (Arqus A12, Qualisys, Sweden) with shared start triggers were utilized to collect Three-dimensional marker trajectory (Qualisys "Twin System" configuration). Two independent computers and Qualisys Motion Capture Sync Units were used to set independent sampling frequencies. The first system captures marker trajectories at 250 Hz and the second system captured at 500 Hz. Custom camera mounting systems were constructed to create six camera pairs <12 inches apart and each camera pair was positioned to optimize data collection for the right lower extremity. Ground reaction force (GRF) data were collected using a force platform (Bertec Corporation, Columbus, OH) sampling at 1500 Hz. GRF data was used to establish signal onset and offset during stance:

Walking: On-set: stepping with the right foot on the force plate. Off-set: right foot completely stepping off of the force plate.

Running: On-set: stepping with the right foot on the force plate. Off-set: right foot completely stepping off of the force plate.

Segment definitions

Three-dimensional trajectories of 28 retroreflective markers were placed on the right shank and right foot, respectively. The right shank was comprised of four anatomical markers located at the fibula head, tibial tuberosity, fibula apex of the lateral malleolus, tibia apex of the medial malleolus, and a four-marker tracking plate. The right foot was comprised of 14 anatomical markers located at the base of the hallux/proximal-distal phalanx, head of the 1st metatarsal, head of the 2nd metatarsal, head of the 5th metatarsal, base of the 1st metatarsal, base of the 2nd metatarsal, the base of the 5th metatarsal, the navicular, sustentaculum tali, lateral calcaneus, medial malleolus, lateral malleolus, inferior calcaneus, superior calcaneus, and a four markers tracking plate place on the lateral aspect of the calcaneus between lateral calcaneus and calcaneal tuberosity. The 14 anatomical foot markers defined the following seven-foot segments (Carson et al., 2001; Leardini et al., 2007; Portinaro et al., 2014):

Hallux (Great toe)

The anterior/posterior axis of rotation (X) is defined using the base of the hallux and head of the 1st metatarsal and the sagittal axis of rotation (Z) is defined using head of the 1st metatarsal and head of the 2nd metatarsal (Figure 1).

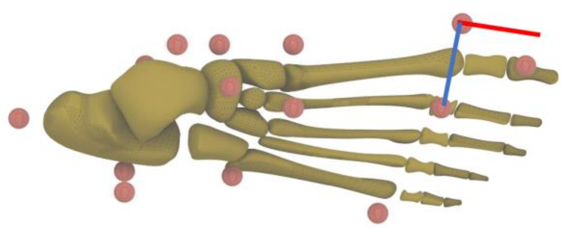

Figure 1

Hallux (Great toe)

Metatarsus (Met)

The anterior/posterior axis of rotation (X) is proximally defined using the base of the 2nd metatarsal and distally defined using the head of the 2nd metatarsal. The sagittal axis of rotation (Z) is proximally defined using the head of the 1st and the head of the 5th metatarsal and distally defined using the base of the 2nd metatarsal (Figure 2).

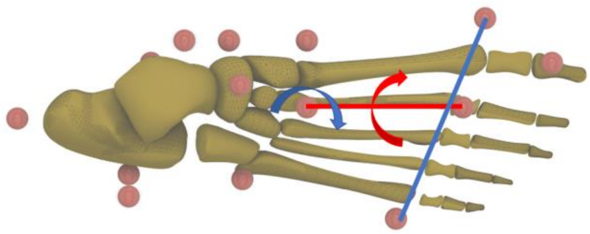

Figure 2

Metatarsus (Met)

Mid-foot (Mid)

The anterior/posterior axis of rotation (X) is proximally defined using mid-point between the base of the 5th metatarsal and navicular and distally defined using the base of the 2nd metatarsal. The sagittal axis of rotation (Z) is proximally defined using mid-point between the base of the 5th metatarsal and navicular and distally defined using the base of the 2nd metatarsal (Figure 3).

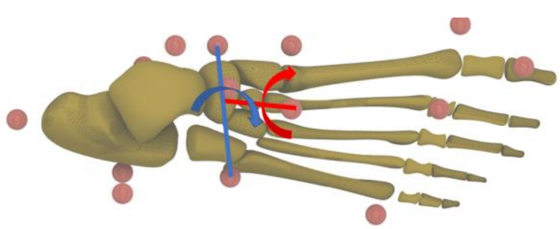

Figure 3

Mid-foot (Mid)

Calcaneus (Cal)

The anterior/posterior axis of rotation (X) and sagittal axis of rotation (Z) were proximally defined using mid-point between the inferior and superior calcaneus and distally defined the ankle joint center projected on a line between the sustentaculum tali and the lateral calcaneus (Figure 3).

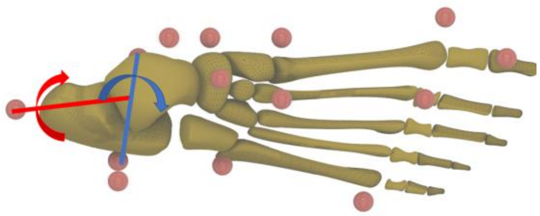

Figure 4

Calcaneus (Cal)

Virtual Foot (Foo)

The anterior/posterior axis of rotation (X) and sagittal axis of rotation (Z) are proximally defined using mid-point between the inferior and superior calcaneus and distally defined using the head of the 1st and 2nd metatarsal (Figure 5).

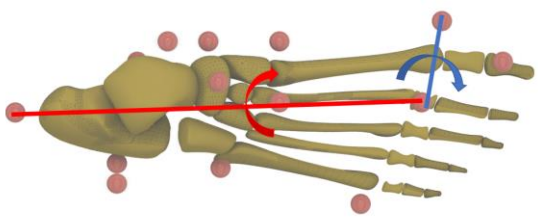

Figure 5

Virtual Foot (Foo)

Participants Preparation

Manual palpations were performed on an athletic training table laying in a supine position where their knee flexed. The foot was prepared using sterilizing swabs then a non-permanent marker was used to identify anatomical landmarks on the foot and shank. Then participants were escorted to the center of the calibrated motion capture volume where neoprene hook and loop wraps were placed on the bulge of the gastrocnemius with 4 (12.7mm) pearl retroreflective markers tracking plate attacked to the lateral aspect of the shank and 6.4 mm pearl retroreflective markers we applied to anatomical locations on the foot and shank.

Experimental procedure

Participants performed static and dynamic trials prior to experimental trials to define body segments. Two static trials where participants stood on the force plate in anatomical position with arms across their chest and two dynamic trials where participants were asked to perform five heel raises. Dynamic movement pattern as used to aid in marker labeling for experimental trials.

Participants stood behind the blue line and on signal, walked at a self-selected pace of 10 m while armed crossed on shoulders, stepping on the force plate placed-mid walkway with the right foot, then continued walking till they are past the other blue line at the end of the walkway.

Participants perform fifteen experimental trials (10 walking and 5 running). The first five walking trails were used as fertilization and control trials with both motion capture systems sampling marker trajectories at 100 Hz. Five experimental walking trials were performed at a participant-selected pace with one system sampling at 250 Hz and the other at 500 Hz. Finally, five experimental running trials were performed at a participant selected pace with one system sampling at 250 Hz and the other at 500 Hz. Trails were considered acceptable if the participant's entire foot impacted the force platform, and no gait abnormalities were observed by the research team (i.e., translational hesitation or stride length alteration prior to the force plate platform).

Data Analysis

Data collected in the Qualisys system were exported as .c3d files and imported into Visual 3D (C-Motion, Germantown, MD, USA.). Kinematic and GRF data were processed with a zero-phase shift fourth-order low-pass Butterworth filter at cutoff frequencies of 10Hz and 50Hz, respectively. The following data collection mean segment range of motion data for each experiment condition were imported into MATLAB (2018a, The Mathworks, Inc., Natick, MA, USA.). Selected dependent variables were analyzed during the stance phase of movement defined by foot contract with the force platform. Initial contact and final contact were defined as the instance where vertical GRF exceeded 10N.

CHAPTER 3

RESULTS

Descriptive data and all paired-sample t-tests results for each experimental condition were presented in Tables 1-4. P values of the t-test results for the three different planes of motion were reported to identify significant differences in range of motion when sampling at 500 Hz for each joint.

Midfoot-Calcaneus joint (cal-mid)

During running trials, mean absolute bias data of the analysis showed that sampling at 500 Hz was found to have a greater cal-mid anterior/posterior range of motion of 4°+-3.6 with statistical significance ($p = 0.02$). Whereas the sagittal and the transverse ranges of motion were at means of 10° ±21° ($p = 0.21$) and 3.5° ±10.6° ($p = 0.38$). During the walking trials, sampling at 500 Hz resulted in a greater cal-mid anterior/posterior range of motion, with a mean of 2° ± 3.3° ($p = 0.13$). Whereas the sagittal and the transverse ranges of motion were at means of 5.5° ±17° ($p = 0.39$) and 5.1° ±10° ($p = 0.89$). In the control trials, sampling at 500 Hz exhibited an increase in the cal-mid anterior/posterior range of motion, with a mean of -3.2° ± 6.2° ($p = 0.19$). The sagittal and the transverse ranges of motion were at means of 6.9° ±22° ($p = 0.41$) and -0.67° ±9° ($p = 0.84$). (Table 1).

Table 1

Midfoot-Calcaneus joint

	Anterior/Posterior			Transverse			Sagittal		
Condition	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value
Control	-3.2	6.18	0.19	-0.67	9	0.84	6.9	22	0.4
Walking	2	3.3	0.13	0.51	10	0.89	5.5	17	0.39
Running	4	3.6	0.02	3.5	10.6	0.38	10	21	0.21

Midfoot-Metatarsus joint

During the running trials, the mean absolute bias data of the analysis revealed an increase in the mid-met transverse range of motion when sampling at 500 Hz, with a mean of 4.3° ± 11.1° ($p = 0.31$). The anterior/posterior and the sagittal ranges of motion were at means of 2.4° ±6° ($p = 0.31$) and 15° ±39° ($p = 0.32$). Similarly, in the walking trials, sampling at 500 Hz resulted in a greater mid-met sagittal range of motion, with a mean of 15° ± 34.4° ($p = 0.27$). The transverse and the anterior/posterior ranges of motion were at means of 3.9° ±17° ($p = 0.55$). and 1.1° ±9.9° ($p = 0.77$) In the control trials, sampling at 500 Hz exhibited an increase in the mid-met transverse range of motion, with a mean of 5.2° ± 15° ($p = 0.36$). The sagittal and the anterior/posterior ranges of motion were at means of 10° ±31.7° ($p = 0.38$) and -0.41° ±2.7° ($p = 0.69$). (Table 2).

Table 2

Midfoot-Metatarsus joint

	Anterior/Posterior			Transverse			Sagittal		
Condition	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value
Control	-0.41	2.7	0.69	5.2	15	0.36	10	31.7	0.38
Walking	1.1	9.9	0.77	3.9	17	0.55	15	34.4	0.27
Running	2.4	6	0.31	4.3	11.1	0.31	15	39	0.32

Metatarsus-Hallux joint

During the running trials, the mean absolute bias data of the analysis revealed an increase in the met-hal sagittal range of motion when sampling at 500 Hz, with a mean of 3.1° ± 6.2° ($p = 0.2$). The transverse and the anterior/posterior ranges of motion were at means of 3.3° ±8.6° ($p = 0.31$) and 4.2° ±11° ($p = 0.33$). In the walking trials, sampling at 500 Hz resulted in a greater met-hal sagittal range of motion, with a mean of 0.54° ± 2.36° ($p = 0.54$). The transverse and the anterior/posterior ranges of motion were at means of -4.7° ±21.6° (p = 0.56). and 0.91° ±11° (p = 0.83) In the control trials, sampling at 500 Hz exhibited an increase in the met-hal anterior/posterior range of motion, with a mean of 5.9° ± 11.5° (p = 0.2). The sagittal and the transverse range of motion were at means of 2° ±4.3° (p = 0.23) and -8.9° ±22.6° (p = 0.3). (Table 3).

Table 3

Metatarsus-Hallux joint

	Anterior/Posterior			Transverse			Sagittal		
Condition	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value
Control	5.9	11.5	0.2	8.9	22.6	0.3	2	4.3	0.23
Walking	0.91	11	0.83	-4.7	21.6	0.56	-0.54	2.36	0.54
Running	4.2	11	0.33	3.3	8.6	0.31	3.1	6.2	0.2

Shank-Foot joint

During the running trials, the mean absolute bias data of the analysis revealed an increase in the sha-foo transverse range of motion when sampling at 500 Hz, with a mean of 4.7° ± 7.5° (p = 0.12). The sagittal and the anterior/posterior ranges of motion were at means of -15° ±38° (p = 0.3). and -0.3° ±8.8° (p = 0.92). Similarly, in the walking trials, sampling at 500 Hz resulted in a greater sha-foo anterior/posterior range of motion, with a mean of -4.7° ± 8.2° (p = 0.15). The sagittal and the transverse ranges of motion were at means of -15° ±36° (p = 0.28) and 4.5° ±30° (p = 0.69). In the control trials, sampling at 500 Hz exhibited an increase in the sha-foo sagittal range of motion, with a mean of -10° ± 24.8° (p = 0.29). The transverse and the anterior/posterior ranges of motion were at means of 8.8° ±24° (p = 0.34) and -1.5° ±7° (p = 0.58). (Table 4).

Table 4

Shank-Foot joint

	Anterior/Posterior			Transverse			Sagittal		
Condition	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value	±Means°	±STD°	P-Value
Control	-1.5	7	0.58	8.8	24	0.34	-10	24.8	0.29
Walking	-4.7	8.2	0.15	4.5	30	0.69	-15	36	0.28
Running	-0.3	8.8	0.92	4.7	7.5	0.12	-15	38	0.3

CHAPTER 4

DISCUSSION

The literature often lacks specific discussions on the optimal sampling frequencies for motion capture technology and how different frequencies may impact kinematic data. Addressing this gap, the objective of this study was to investigate the influence sampling frequency has on the kinematics of a multi-segment foot model during walking and running. By examining the impact of varying sampling frequencies, this study aims to enhance our understanding of the methodological considerations associated with kinematic data acquisition.

Analyzing joint angle differences, our finding shows a significant increase in the anterior/posterior range of motion when sampling at 500 Hz in the Midfoot-Cal joint during running trials ($p = 0.02$) (Figure 6). However, during walking and control trials no significant differences were found in the range of motion when sampling at 500 Hz. Other notable differences in the range of motion were observed in the Metatarsus-Hallux joint, where results showed a trend of approaching significance: sampling at 500Hz showed increased anterior/posterior range of motion at ($p = 0.2$) in running trials (Figure 7), while walking trials showed a sagittal range of motion at ($p =0.54$) (Figure 8). Other than that, there were no significant differences in the range of motion when sampling at 500 Hz.

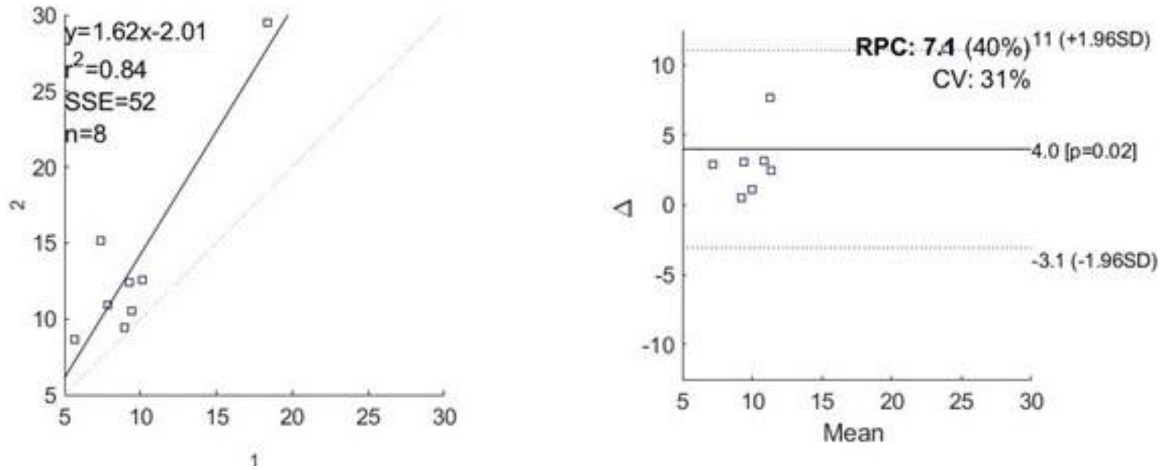

Figure 6

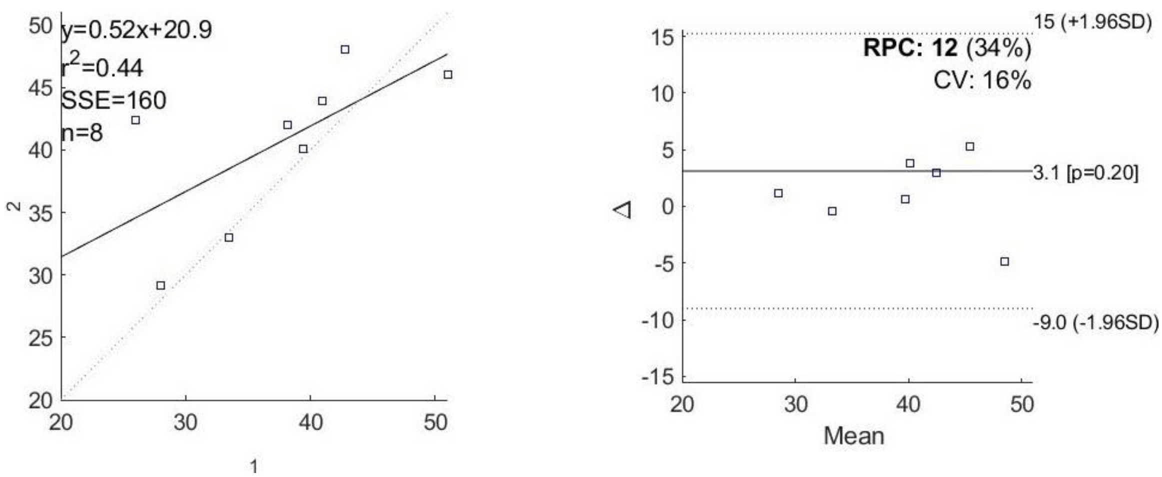

Figure 7

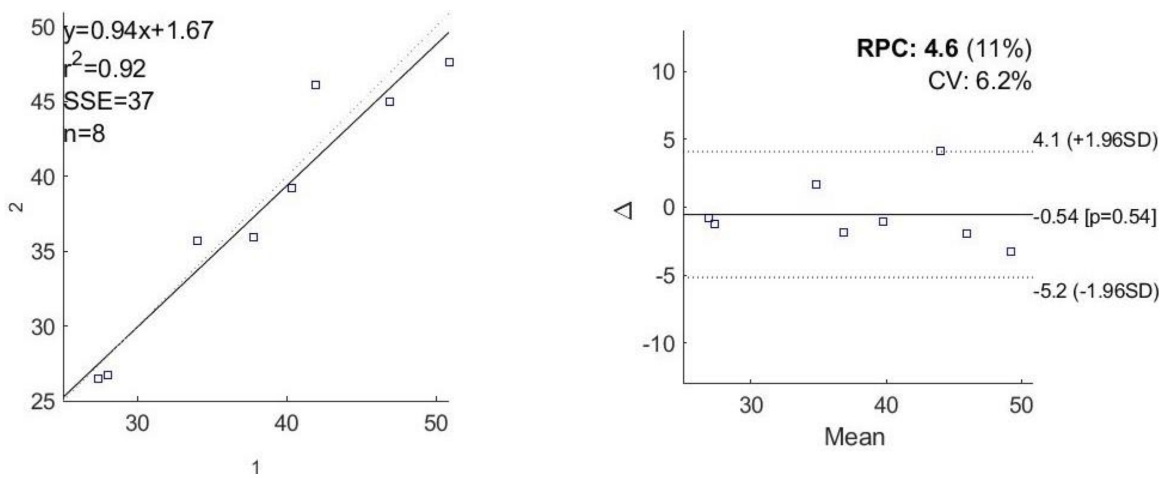

Figure 8

These findings suggest that capture at a higher sampling frequency may show a greater range of motion than at lower sampling frequencies. A past research study aimed at investigating the differences between cushioned and uncushioned running shoes on foot kinematics data showed that during trials Midfoot-Cal joint using motion capture system at 200 Hz sampling frequency (named MF-RF corresponding to Midfoot, Rearfoot in the study) no significant differences were notable in the range of motion (Langley et al., 2016). Looking at our findings, capturing data at a higher frequency of 500 Hz saw a greater range of motion in that same joint. This suggests that the Langley et al., 2016 might have had more significant differences in the range of motion in the Midfoot-Cal joint had the data been captured at a higher frequency.

The purpose of this study is to use motion capture technology to see if collecting lower extremity data at variable frequencies had any effect on kinematic data. Though there was some noticeable greater range of motion in the Midfoot-Cal joint, and trends showing results nearing significance in the Metatarsus-Hallux joint, the overall results did not show statistical significance when sampling at varying frequencies. The lack of significance in running trials might be due to factors such as that during running trials participants showed hesitation to run due to the fear that they might slip and fall while trying to place their right foot on the pressure plate. Another limitation is sample size, which might have prevented results to show significant differences. Future studies should focus on investigating sampling at higher frequencies when it comes to comparing joints' range of motion during running versus walking, the results might show that sampling at a higher frequency demonstrate greater differences at increased acceleration.

In conclusion, this study has started to draw focus on the effect sampling frequencies has on lower extremity kinematic data, demonstrating that capturing data at higher frequencies might show greater range of motion. However, more research is required to further investigate the effect of varying sampling frequencies on kinematic data to achieve optimal data processing.

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To: Mohammed Alsanounah

From: M. Daniel Becque
Chair, Institutional Review Board

Date: February 21, 2023

Title: *The influence optical motion capture sampling frequency has on data collection of common task kinematic data*

Protocol Number: 23032

The above referenced study has been reviewed and approved by the SIUC Institutional Review Board under an expedited category.

This approval by Southern Illinois University IRB on **February 21, 2023** is considered active. The following IRB policies apply to protocols approved in expedited categories :

- Changes or modifications to the protocol, regardless of how minor, must be submitted for IRB review and approval prior to implementation, except to eliminate immediate hazard to subjects.
- Promptly report adverse events, off- protocol activities, or other noncompliance to the IRB within 5 business days. Contact the IRB for further guidance.
- The IRB will request an annual update each year the project remains active. Update forms must be received by the due date provided to maintain active status.
- This approval is valid only for as long as you are a student or employee of SIUC.
- The Principal Investigator is responsible for reporting study closure to the IRB in a timely manner. Please contact the IRB for a study closeout form when research activities are complete. A study is considered complete when you are no longer enrolling new participants, collecting or analyzing data.
- As always, you are responsible for compliance with Southern Illinois University Carbondale policies and procedures. If you have any questions or require further information, please contact the Institutional Review Board Office via email siuhsc@siu.edu or via phone at 618-453-4530.

Best wishes for a successful study.

This institution has an Assurance on file with the USDHHS Office of Human Research Protection. The Assurance number is 00005334.

MDB:eb

Cc: Sean Quisenberry

Revised 11-24-2021

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