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UNIVERSITY OF CALGARY

Usability of Markerless Motion Capture for Conducting 3D Instrumented Gait Analysis with Children

by

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A THESIS

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Abstract

Three-dimensional gait analysis (3DGA) provides important data for informing clinical decisions for children living with cerebral palsy and other mobility impairments. However, marker-based motion capture —the current clinical standard for conducting 3DGA— may be uncomfortable or even intolerable for many children. Marker-based assessments require the accurate placement of reflective markers on bony landmarks, which requires participants to wear tight clothing or clothing with a waistband that can be rolled down enabling markers to be placed on the pelvis. Marker placement can be time-consuming, especially for participants with non-typical anatomical development, increasing their fatigue level throughout the assessment.

Markerless motion capture technologies that utilize computer vision to identify key landmarks may increase the patient-friendliness of 3DGA. The purposes of this research were to a) compare markerless technologies with marker-based technologies for 3DGA with pediatric populations including those with mobility impairments, and b) to determine the factors that impact the usability of markerless motion capture for clinical gait assessments. The first study concurrently compared a markerless motion capture system to a marker-based system. Our results indicated that markerless and marker-based motion capture had good agreement in the sagittal plane for pediatric populations with and without mobility impairments. The second study investigated the impact of clothing on kinematic data when markerless systems are used, explored participant and caregiver perceptions of 3DGA, and assessed the time required to complete a markerless assessment. We found that many clothing styles had minimal impact on the kinematic data; however, clothing that was baggy or obstructed the joints reduced data quality. Our participants preferred completing markerless assessments as they could wear their own clothing, did not have to have markers placed, and appreciated the brevity of the assessment. This study combined with the literature, provides good evidence that markerless motion capture is an accurate method of assessing joint angles in the sagittal plane of children with and without mobility impairments that enables a more participant-friendly assessment.

Preface

This thesis is an original, unpublished, and independent work by the author, A. Rande. The experiments described in chapters three and four were covered by ethics certificate REB22-1481, issued by the University of Calgary Conjoint Health Research Ethics Board.

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Dedication

To my mom, the woman who would move mountains to see me succeed and who encouraged and inspired me to break barriers and shatter glass ceilings. Thank you for always pushing me to be the best version of myself and supporting me when I struggle. I could not have done this without you.

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List of Abbreviations

Abbreviation	Definition
3D-GA	Three-Dimensional Gait Analysis
3D-IGA	Three-Dimensional Instrumented Gait Analysis
AFO	Ankle-Foot Orthosis
AI	Artificial Intelligence
ASIS	Anterior Superior Iliac Spine
COG	Centre of Gravity
CP	Cerebral Palsy
CPG	Central Pattern Generator
C3D	Coordinate 3D
FAQ (FAQ-10)	Gillette Functional Assessment Questionnaire
FMS	Functional Mobility Scale
GMFCS	Gross Motor Function Classification System
GRF	Ground Reaction Force
HBM	Human Body Model
HICCUP	Healthy Infants and Children Clinical Research Program
IQR	Inter-Quartile Range
MAE	Mean Absolute Error
MB	Marker-Based Motion Capture
MDC	Minimal Detectable Change
ML	Markerless Motion Capture
Q1	First Quartile or 25th percentile

Q3	Third Quartile or 75th percentile
RMSD	Root-Mean-Square Deviation
ROM	Range of Motion
SEMLS	Single-Event Multi-Level Surgery
TD	Typically Developing

Chapter 1: Introduction

1.1 Problem Statement

Three-dimensional instrumented gait analysis (3D-IGA) is an important component of informing clinical decision-making for children with cerebral palsy (CP) and other mobility impairments (1-5). When 3D-IGA is used to inform and plan orthopedic surgeries patients, surgical methods can be tailored or modified for better surgical outcomes, less follow-up surgeries may be required, and patients may have a better post-operative outcome (6). Three-dimensional gait analysis is also used for informing non-surgical treatment —prescription of botulism toxin and orthotic devices— and to track rehabilitation progress(2, 7). Traditionally, 3D-IGA are conducted with marker-based (MB) motion capture systems which require the careful palpation of bony landmarks for the placement of reflective markers. Marker placement requires the children to wear tight clothing or clothing that can be taped to expose the necessary bony landmarks (i.e. anterior superior iliac spines (ASIS) and sacrum). This may be time-consuming as data quality is highly sensitive to the accuracy of marker placement. The required clothing and careful palpation may be intolerable for children with sensory disorders, exhausting for those who fatigue quickly, and not acceptable for those who prefer to wear modest attire. For these reasons, marker-based data collection may negatively impact the experiences of children and their families, creating a barrier to the accessibility of 3D-IGA. This, then, may limit the populations for whom this important tool can influence care.

Markerless (ML) motion capture systems utilize computer vision to identify key anatomical features without the placement of reflective markers (8, 9). Computer vision uses supervised learning and neural networks to train an artificial intelligence (AI) algorithm to detect landmarks, thus, removing the need to palpate sensitive areas such as the pelvis for marker placement, which may decrease the burden for children who require 3D gait analysis. In healthy adults, ML systems have been validated against traditional MB methods with kinematic outputs showing good agreement (10) and good inter-session repeatability with stable spatiotemporal parameters (11). Few studies have investigated ML methods with pediatric populations. There is preliminary evidence for the concurrent validity of ML technologies for children with cerebral palsy; however, it has not yet been validated for use in typically developing children. Only a few studies have examined the usability or impact of using ML technologies with children with cerebral palsy or other mobility impairments.

1.2 Research Purpose

The research aimed to investigate the accuracy of markerless motion capture for pediatric populations, including those with mobility impairments, and to determine the factors that impact the usability of such systems in pediatric populations.

1.3 Research Questions

The following research questions will be addressed in two studies:

1. Is markerless motion capture accurate when conducting three-dimensional clinical gait analysis with typically developing children and children with mobility impairments?
    a. Do three-dimensional gait assessments completed with a markerless approach produce results similar to those completed with the current standard marker-based approach?
2. What is the usability of markerless motion capture methods for typically developing children completing three-dimensional gait analysis?
    a. Does markerless motion capture produce consistent kinematic (joint angles) data across clothing conditions?

b. What are the participant and caregiver perceptions of markerless and marker-based three-dimensional gait analysis?
c. How long does it take to conduct a markerless assessment compared to a marker-based assessment?

1.4 Rationale

The data collected during a three-dimensional gait assessment (3D-GA) can have broad and important implications on clinical decision-making for children with cerebral palsy and other mobility impairments. Kinematic data are frequently used to inform surgical decision-making — single-event multi-level surgery (SEMLS) (4) —, prescription or modification of orthotic devices (e.g. ankle-foot orthoses), and the creation of goals for rehabilitation plans conducted by physical and occupational therapists. Three-dimensional gait assessments provide highly sensitive data that can be used to track changes pre- and post-interventions and across maturation, providing key insights into how a child is ambulating. Although this gait analysis technique is very important in clinical settings, some patients are unable to complete a 3D-GA. The inability to complete a 3D-GA may be caused by sensitivities or discomforts with marker placement, the use of gait aids or orthoses that block reflective markers, or the inability to ambulate far enough for data collection —literature suggests that at least three to five trials should be collected to minimize random errors and ensure consistent results are produced (12, 13)— to be accurate or reliable. In these cases, clinicians are reduced to using two-dimensional or visual methods to assess how a child ambulates. Limitations of visual methods of gait analysis include being less sensitive than instrumented systems, challenges in determining motion at the hip, and the impact of the assessor's experience level on the quality of the assessment (14). The limitations of marker-based methods include inaccuracies caused by skin movement artifact (15), inaccurate marker placement (16), adiposity around bony landmarks, and marker occlusions when gait aids are present; participant discomfort; and time required to complete an assessment. Markerless motion capture may be an effective way to reduce the limitations associated with current motion capture techniques; however, ML needs further validation and exploration to confirm its impact on these limitations.

The popularity and accessibility of markerless motion capture technologies have increased in the last several years. Several studies have investigated the accuracy and reliability of these systems in healthy adult populations (10, 11, 17). However, pediatric populations have largely been neglected in the literature. It is important to validate ML technologies in children as it cannot be assumed that the computer vision software has been trained to identify landmarks on children or that it will work with the smaller stature of children.

The validation of ML systems could be an important step to decreasing the patient burden of 3D-GA but is not the only important measure to consider before the systems are implemented in clinical settings. Understanding how the patients and their caregivers feel about the assessments they complete is an important part of clinical care that has largely been ignored for clinical gait analysis. Previous studies have investigated clinicians' perceptions and the factors that impact the adoption of 3D-IGA in clinical settings (18-20), but there is no known literature investigating how the patients and their caregivers perceive the assessments. Determining the usability of ML 3D-IGA compared to the current MB system is important for understanding the patient impact the new system could have.

This thesis will extend the evidence informing concurrent validity to pediatric populations and includes the first study to evaluate factors influencing the usability of markerless systems in pediatric populations.

1.5 Summary of Thesis Format

This MSc thesis investigates the usability of a markerless motion capture system compared to the current gold standard marker-based motion capture system for pediatric populations with and without mobility impairments. The structure of this thesis is as follows: this chapter provides a general introduction and description of the research objectives. The second chapter includes an overview of the patient population and a review of relevant literature. The third chapter includes a study which concurrently compares a markerless motion capture system to a marker-based system in two distinct pediatric populations. The fourth chapter includes a study which examines the usability of markerless motion capture by examining the consistency of the system's kinematic outputs across clothing conditions, investigating the participant and caregiver perceptions towards markerless and marker-based assessments, and evaluates the time commitment required for completing a markerless assessment compared to a marker-based assessment, and provides a set of recommendations for what children could wear during three-dimensional gait assessments if markerless systems are used. The fifth chapter provides an overall summary of the research, an overarching conclusion with potential implications of the results, and recommendations for future research.

Chapter 2: Literature Review

2.1 Gait

Typical human gait follows a cyclical pattern that is broken down into phases and events (21). Due to the cyclical nature of gait, a cycle is defined to originate at initial contact of one foot and end when the same foot contacts the ground again. During the typical gait cycle, the body cycles between single-limb and double-limb support phases. In the single limb support phase — around forty percent of the gait cycle— only one foot is in contact with the ground and is bearing the entire weight of the body, while the double limb support phase —around 20% of the gait cycle— occurs when both feet are contacting the ground (21). Initial contact is the initiation of stance phase (double limb support); stance phase is the larger proportion of the gait cycle, encompassing nearly sixty percent of the cycle. Stance phase is defined as the period of gait where the foot is in contact with the ground and is further broken into five subphases and events in the gait cycle: initial contact, loading response, midstance, terminal stance, and pre-swing. Swing phase represents forty percent of the gait cycle and is the period where the foot is not in contact with the ground. This phase begins when one foot is lifted from the ground and ends just before initial contact. The swing phase is identified by three sub-phases: initial swing, mid-swing, and terminal swing.

Gait characteristics and the determinants of gait play a key role in understanding how gait changes across the lifespan and in the presence of pathological conditions. There are six determinants of gait —foot and ankle mechanisms, early knee flexion, late knee flexion, pelvic rotation, pelvic tilt, and pelvic lateral displacement— that are used to define gait efficiency (22). It is theorized that typical gait will be efficient when the displacement of the centre of gravity (COG) is minimized, enabling the successful shift through weight acceptance, single limb support, and limb advancement in a smooth cycle (21). Throughout the gait cycle, the hips, knees, and ankles move through a specific range of motion in three planes (sagittal, frontal, and transverse).

2.1.1 Neurological Control of Gait

Much of the control of gait is unconscious with less involvement of the cerebral cortex than many other less cyclical voluntary movements (e.g. reaching).

A predominant theory in human locomotion is that gait is mediated by central pattern generators (CPG) in the spinal cord that generate the typical gait pattern during typical walking conditions (23). These circuits produce pairs of excitation and inhibition in agonist and antagonist pairs of muscles in a cyclic pattern. Human locomotion requires a delicate balance of sensory feedback and CPG activity to create the typical gait pattern and prevent falls (24). Evidence of CPGs in humans is indirect as direct methods are invasive and would not be ethical. The bulk of the research on CPGs and human locomotion utilized decerebrate cats —cats that no longer have cerebral function due to severing of the brainstem; therefore, removing certain reflexes and sensory feedback— or indirectly tested the theory with humans with spinal cord injuries.

When walking in new environments, on challenging terrain, or when learning to walk (developing motor skills) the cerebral cortex, brainstem, and cerebellum are activated and work alongside sensory feedback and cognitive postural control to generate the cyclical gait pattern including modulating the CPGs (23). Simple motor commands reach the muscle via the peripheral nervous system’s alpha motor neurons which receive monosynaptic input from the corticospinal tract originating in the primary motor cortex (25). Activity in alpha motor neurons is also modulated by spinal circuits (including CPGs) and other descending motor tracts (e.g.

from the brainstem —such as the mesencephalic motor region and cerebellum (23, 24)). Activity in the primary motor cortex is moderated by other motor and sensory regions (e.g. premotor area, supplementary motor area, prefrontal area, cerebellum, primary sensory cortex, thalamus)(25).

2.1.2 Gait Maturation

In typical development, in the fourth year of life, the neurological basis of gait is developed; however, mature gait is not achieved until the early teen years when lower limb growth ends. The age of gait maturation is sex-dependent with females reaching gait maturation around two years before their male counterparts —13.2 years in females and 15.6 years in males— (26). During maturation there are five key gait characteristics that greatly change: 1) duration of single-limb stance, 2) walking velocity, 3) cadence, 4) step length, and 5) width of base of support. These characteristics are sex-dependent with females having shorter step lengths and a narrower base of support (26), there are also known anatomical and kinematic differences such as increased pelvic rotation and obliquity, greater hip kinematics in all planes during the loading phase, and increased ankle plantar and dorsiflexion (27, 28). Gait changes throughout childhood and early adolescence with predictable changes at certain developmental stages (e.g. mature cadence occurs after lower limb maturity) (26).

2.1.3 Pathological Gait

There are predictable changes to the human gait pattern throughout the lifespan. As we age, our gait becomes slower with a reduced step length, this can be impacted by muscle weakness, visual impairments, and an overall reduction in balance and coordination (29). Not all abnormal gait patterns are considered pathological. Pathological gait occurs when there is a neuromuscular or musculoskeletal impairment that results in mechanical compensation while walking. A physical exam and medical history must be taken to understand and diagnose pathological gait as there are multiple aetiologies that can contribute to the observed patterns (e.g. upper motor neuron lesion, lower motor neuron lesions, musculoskeletal injury), with different secondary impairments that can cause further deviations (30).

2.1.4 The Impact of Observation on Gait

When individuals are observed our actions change. This phenomenon is known as the Hawthorne effect. Adaptations to how humans behave when observed can impact the collection of accurate and reliable gait data in both clinical and research environments. Several studies have investigated the impact of the Hawthorne effect on various gait parameters, with many studies evaluating the impact on spatiotemporal parameters (i.e. gait speed, cadence, step length).

One study utilized a two-condition protocol where participants were told the trial had begun and were requested to walk to the end of the walkway (over condition). At the end of the walkway, they were told the trial had ended and were asked to return to the starting line. The research team recorded their walk back to the starting line —in this trial the participants were unaware that they were being observed (covert condition)— and to wait for the next trial to start. The study found that gait speed and step length decreased when the participant was aware they were being measured while cadence increased (31). The study also noted that the greatest impact of observation (gait speed difference between overt and covert conditions) occurred in the young (21 to 37 years old) healthy control group (31). Another study investigated the impact of the number of researchers present in the lab with changes in spatiotemporal parameters. Participants walked in the lab a) without any research personnel, b) with a few research personnel, and c) with a large group of research personnel (32). The study found a strong positive correlation between the number of researchers/observers in the lab with changes in gait speed, cadence, and stride length, and a negative correlation with step duration (32).

A study completed on a group of young female participants found similar results as the previously mentioned studies when examining spatiotemporal parameters; however, this study also found a notable difference in the kinematic and kinetic data (33). They found an increase in the range of motion (ROM) of the right hip and left ankle and a greater ground reaction force (GRF) during push-off when the participants were aware they were being observed (33).

When analyzing gait data, it is important to understand the potential impacts to the individual's gait caused by the researcher observing them. Data collected in a research or clinical setting may differ from the individual's true gait pattern with significant changes (increasing or decreasing) to their gait speed, cadence, step length, joint ROM, and their GRF.

2.2 Cerebral Palsy

Cerebral palsy (CP) is one of the most common neuromotor impairments and is the most common cause of childhood physical disability impacting 2 to 3 per 1000 children (34, 35). CP is a heterogenous group of permanent conditions caused by a non-progressive lesion to the brain occurring during fetal development or within the first two years of life, impacting the child's posture or movement (36, 37). The motor disability related to CP frequently presents as limited motor control, muscle weakness, and spasticity (1). Due to the diversity of the impairments, children with CP experience a wide range of functional abilities. The Gross Motor Functional Classification System (GMFCS) is used to categorize a child's motor abilities like sitting, standing, and ambulation and their need for assistive devices. Children are categorized into GMFCS levels I through V, with I indicating that the child can walk independently while a score of V indicates a severe motor disability where the child will use a wheelchair pushed by another individual to mobilize. More than 70% of children with cerebral palsy are GMFCS I-III and can walk with or without hand-held mobility aids (38).

For ambulatory children with cerebral palsy, their motor impairment impacts their walking ability. There are many intrinsic and extrinsic factors that impact how individuals with CP ambulate. Intrinsic factors include things such as energy expenditure, fatigue, pain and discomfort with walking. Extrinsic factors are related to how they are perceived by the public and the judgement they feel when walking with gait aids or with pathological gait patterns (39). Rehabilitation goals and outcomes frequently revolve around increasing or maintaining the ability to walk as participation in physical activity and quality of life are linked to walking ability (40). Many adults with CP report a reduction in independent walking and an increased fear of falling. This may lead to the increased use of gait aids or wheelchairs to increase comfort and reduce risk (39).

2.2.1 Pathological Gait in CP

The motor disability including muscle weaknesses experienced by children with CP can lead to pathological gait patterns. These patterns are defined by degree of deviation and by level of involvement; however, not all children with CP face the same impairments or set of impairments and their gait may not be defined strictly within the pathological categories attributed to CP. There are key differences in gait pathology for hemiplegia (affects one side of the body) and diplegia (affects both legs) with four main pathological gait patterns attributed to each. Spastic hemiplegia has four main categories: drop foot, true equinus, true equinus with recurvatum knee, true equinus with jump knee, and type IV which is described as equinus with jump knee and a flexed, adducted, and internally rotated hip (41). Spastic diplegia patterns are crouch gait, jump gait, true equinus and apparent equinus (1). Due to the predominant distal involvement common among people with hemiplegia, true equinus is the most common pattern while the proximal involvement observed in the diplegic populations causes crouch gait and apparent equinus to be the most common patterns (41).

2.2.2 Use of 3D-IGA for Children with Cerebral Palsy

Pathological gait patterns are typically diagnosed using instrumented gait analyses (IGA) where a variety of technologies (marker-based motion capture, force plates, electromyography, etc.) are used to quantitatively define joint motion during gait. For children with CP, gait analyses are important clinical assessments that inform the structure of rehabilitation plans, modifications to orthotic devices, and surgical decision-making (2, 6, 18). Single-event multi-level surgeries (SEMLS) are commonly prescribed for children with cerebral palsy to correct multiple —at least four— anatomical abnormalities in both lower limbs during one surgical operation (42). Evidence supports the use of clinical gait analysis to inform surgical decision making and has indicated some positive impacts on surgical outcomes and the use of 3D-IGA was shown to decrease the overall number of surgical procedures recommended and completed which may impact the quality of life for the patient (4, 43). A systematic cost analysis determined that the use of instrumented gait analysis in the treatment of children with cerebral palsy reduces the long-term cost of treating children with CP, as those who completed a 3D-IGA had less surgeries after completing the 3D-IGA-guided surgery (44). When 3D-IGA is used to inform surgical decisions and rehabilitation plans, the need for repeat procedures decreases; therefore, decreasing the overall healthcare time and cost for the child. Spending less time recovering from surgery and more time ambulating can increase the child’s quality of life.

2.3 Marker-Based Motion Capture

Three-dimensional instrumented gait analysis (3D-IGA) used in a clinical setting, sometimes called 3D-GA or clinical gait analysis uses a variety of technologies to gather quantitative information on how an individual walks. Optoelectronic measurement systems also known as marker-based motion capture systems are the currently accepted clinical standard. Optoelectronics use active or passive markers and cameras to track joint segments during gait. Active markers are affixed to specific bony landmarks and utilize built-in LEDs which flash in specific sequences or frequencies —this provides advantages for identification but carries a much higher cost for the system— for joint centre detection. Passive markers are small reflective spheres affixed to specific bony landmarks while the camera system projects infrared light that is reflected by the markers, the reflected light is captured by the camera creating a set of moving markers on the data collection software where marker location is determined as the location of the intersection of the light rays.

2.3.1 Limitations of Marker-based Motion Capture

Although marker-based motion capture is considered the current standard, it is not a true gold standard measurement technology as there are several common errors that occur when using this method. Markers are susceptible to soft tissue artifact (16), incorrect marker placement (16), occlusions (45), and are not always well tolerated by children.

Soft tissue artifact or skin movement artifact can cause significant errors when using marker-based motion capture. Markers are placed on the skin after the careful palpation of bony landmarks; however, movement of the skin relative to those bony landmarks when the participant is in motion can cause the marker to track in the wrong position. Soft tissue artifact is more likely to occur and increase errors in individuals who have a greater body mass or increased adiposity and in those with loose skin — soft tissue artifact causes deviations in knee kinematics with large angular displacement during both stance and swing in the thigh and shank segments (15)— these errors can negatively impact surgical and other treatment plans.

The placement of the markers to the correct bony landmarks requires an expert. Careful palpation of the body must be completed to ensure the markers are placed in the correct location. Displacing a marker by 10mm can cause large differences in the data output. For example, incorrect marker placement on the anterior iliac spines (ASIS) can cause the pelvic model to appear rotated and tilted on a healthy typically oriented pelvis (46), and misplacement of the knee markers in the anterior-posterior direction greatly impacts joint angles at the ankle, hip (in the transverse plane) and knee (in the sagittal plane) (47). High variability exists across centres and between raters with the highest inter-rater reliability in the sagittal plane and the lowest reliability and highest error rate observed for hip and knee rotation (13). With high variability observed in inter-trial and inter-session testing, re-assessing gait can be difficult when using marker-based systems, even though test re-test reliability improves with more marker placement experience, the amount of variability can make it challenging to compare gait at different time points (48).

Marker occlusion is a common error in marker-based motion capture with partial occlusions being more common when passive markers are used. The passive markers reflect the infrared lights, and the marker location is denoted as the cross-section between all the light rays. The light rays can be partially or fully blocked or skewed (45). A full occlusion occurs when either the infrared light cannot reach the marker or the reflection from the marker is blocked, this can occur due to rotation of the clothing blocking the marker or the use of large gait aids. In these instances, the marker is not tracked and data from this marker is lost, many motion capture systems enable the manual interpolation of the missing markers to prevent data loss. Partial occlusions can cause errors within the data as the intersection of the reflections may cause the centre of the marker to be identified in a rotated or incorrect position. This can cause makers to have an offset of up to 7.20mm, an offset of this magnitude would greatly impact the kinematic and spatiotemporal data (45).

For children with bony abnormalities and neuromotor impairments (e.g. Cerebral palsy), three-dimensional clinical gait analyses are frequently conducted throughout development to inform surgical decision-making, fitting and adapting of orthoses, and creating rehabilitation plans. However, marker-based motion capture is not an inclusive method for conducting 3D-GA and may limit the ability of children with sensory, cognitive, and behavioural impairments to complete the assessment. For markers to be placed, children are required to wear tight clothing or clothing that can be taped to expose the bony landmarks at the pelvis —ASIS and sacrum—, thus excluding children who are part of religions where conservative clothing is required or those who wear modest attire. The required clothing and palpation of the pelvis may also make individuals, especially those with body dysmorphic disorders feel uncomfortable. For individuals with cerebral palsy, standing still for long periods of time (as required for marker placement) may increase fatigue and pain in the lower limbs. The time it takes to place markers may be increased for some children with cerebral palsy and other mobility impairments as their bones may be oriented differently than what is typically expected. When placing markers on individuals with differing anatomy locating their bony landmarks can be challenging and time-consuming.

2.3.2 Current Practices for Clinical Gait Analysis

A recent survey of 97 gait laboratories across 16 European countries explored how gait labs operate (49). The most common diagnoses assessed in the gait labs are cerebral palsy, neuromuscular disease, and stroke. Many gait labs assess children (15%) and adults (25%) — 59% of gait laboratories assess children and adults. The median time to complete a 3D-GA was 100 minutes, 50 minutes was spent with the patient —20 minutes for patient preparation like marker placement and 30 minutes for data collection— and another 50 minutes was spent analyzing the data and creating the gait report. After the gait report is generated, a multi-disciplinary team meets to decipher the results and discuss the clinical plan. The study reported that differences in the motion capture software, marker model used, and data collection protocol made it challenging to compare results from different labs (49).

2.4 Markerless Motion Capture

Markerless motion capture is a relatively new method for conducting three-dimensional gait analyses without reflective markers. Markerless motion capture systems use computer vision and deep learning algorithms to analyze 2D or 3D motion of the human body.

The many limitations and errors related to marker-based motion capture systems have led to the development of new technologies that do not require markers to be placed on the skin. OpenCap, OpenPose, DeepLabCut and Theia3D are a few software options available to capture motion data. However, to be used clinically for instrumented gait analysis there are a few key requirements: local data storage, compatibility with other instruments, accurate joint detection, and the ability to calculate 3D motion. Privacy is a priority when working with vulnerable populations, all identifiable data gathered during the gait assessments must be stored securely and not shared through a cloud outside of the healthcare system to ensure patient’s anonymity is maintained. OpenCap requires all video data be uploaded to the cloud where it is analyzed at Stanford University; the lack of privacy protections eliminates it as a potential tool in many clinical settings. OpenPose is limited by its single camera model and can only compute sagittal plane data and is not compatible with other instruments (e.g. force plates or EMG). DeepLabCut requires training on the dataset provided, this can be inconsistent as labelling may be inaccurate, thus providing poor data overall. To our knowledge, Theia3D is the only software that meets the constraints required for collecting three-dimensional data in a clinical setting.

2.4.1 Theia3D

Theia3D is a Canadian markerless motion capture software. The software utilizes deep learning-trained algorithms to identify a proprietary set of salient features of the human body frame-by-frame to produce a 3D 4x4 pose matrix where the position and orientation of each identified landmark is listed. Theia3D is a post-processing software where videos from synchronized video cameras are uploaded, a skeleton is scaled to fit the individual and 17 rigid body segments are tracked and used to solve the 3D pose using inverse kinematics. Theia3D is directly compatible with biomechanics software (Visual3D) where kinetic data can be uploaded and synchronized to the kinematics to analyze ground reaction forces (GRF) and other gait characteristics. Theia3D can work with six or more digital cameras and calibration requires a checkerboard to be shown to three cameras at a time. Theia3D can be used with multiple high-speed video cameras (e.g. Sony RX0II, Vicon and Qualisys cameras), thus enabling a broad range of gait labs to investigate the usability of the technology as many labs already run on Vicon or Qualisys systems and the cost of the Sony cameras are more affordable than many other camera options

Theia3D could increase the accessibility of three-dimensional gait analysis for individuals with sensory impairments or those who do not wish to wear tight and revealing clothing —required for marker-based analyses— as minimal physical contact from the assessor is required and the child can wear a broader range of clothing. This could increase the number of children utilizing instrumented gait analysis providing their clinicians with more quantitative data to aid in clinical decision making.

2.4.2 Validation of Theia3D

Concurrently validating a new system against the current standard requires clear definitions and outlines of what is deemed acceptable. Literature investigating the validity of markerless technologies —more specifically Theia3D— have used statistical guidelines such as root-mean-square deviations (RMSDs) and mean absolute error (MAE). Initial investigations into the accuracy of Theia3D have been largely conducted in a population of healthy, recreationally active adults and used an RMSD value of less than 5º as their cut-off for assessing validity.

The reliability of marker-based systems is well established and can be used as a guideline for determining the accuracy of markerless systems. The inter-rater inter-session reliability of a marker-based system relies heavily on the accurate identification of bony landmarks for marker placement. For clinical interpretation, it is key that the changes observed in the kinematics are related to the actual physical change of the participant and not error introduced by differences in marker placement. The minimal detectable change (MDC) quantifies the change observed that is not caused by error within the measurement system. In healthy young adults, MDCs of greater than 5º were observed in the sagittal and frontal planes of the knee and hip, while around 4º was observed in the sagittal plane of the ankle (50). Therefore, when determining the accuracy of a markerless system differences of less than 5º should be accepted at the knee and hip and only 4º at the ankle.

2.4.2.1 Adults

Literature investigating the accuracy and repeatability of Theia3D for a healthy adult population concurrently compared to a standard marker-based system has shown excellent agreement for spatiotemporal parameters. Spatiotemporal parameters (including gait speed, step length, stride length, stride width, step time, cycle time, swing time, stance time, and double-limb support time) were calculated concurrently with Theia3D and a marker-based system. Gait speed between systems was determined to be nearly identical with excellent agreement (mean difference of 0.00m/s)(11). Root-mean-square deviations between the two systems when comparing lower body kinematics were acceptable (mean < 5° of deviation, as marker placement errors within the lower limb can contribute to around 5° of error both inter-trial and inter-rater(10, 12)) with greater differences between the two systems being observed in the knee and ankle (11). Knee adduction with the markerless system was greater than in the marker-based system during the swing phase and ankle inversion and eversion during stance phase resulted in a higher RMSD than the other kinematic measures (11). When examining the repeatability of gait outcomes in adults with osteoarthritis, mean segment differences of the pelvis, hip, and foot indicated good inter-trial and inter-session variability, while the thigh and shank segments had greater variabilities (51).

A study found that clothing condition had no meaningful impact on segment length, spatiotemporal parameters, and joint angles with healthy, recreationally active adults (52). However, the length of the thigh segment differed between the two clothing conditions and showed low agreement (52). This segment difference likely created a cascading error that impacted measures of the knee as the study found the largest variation in joint angles —resulting in higher RMSDs— at the knee.

When implemented in community settings, Theia3D had good reliability with RMSDs between 0.96º and 3.71º observed between sessions (53). Good to excellent agreement was observed between a pressure-sensitive walkway and Theia3D for measures of cadence, speed, step length, stride length, and stride time, indicating that Theia3D may be a feasible method of gathering quantitative data in clinical and community settings (54).

The above literature provides good preliminary evidence of concurrent validity, reliability, and repeatability of Theia3D; however, all of the evidence was collected in adult populations.

2.4.2.2 Pediatric Populations

There is limited literature investigating the use of Theia3D in pediatric populations. To our knowledge, only two papers to date have concurrently compared Theia3D to marker-based systems. One study concurrently compared Theia3D to a marker-based system in a group of typically developing (TD) children and a group of children with spastic cerebral palsy (CP) (55). The study found a systematic offset of 5º in the sagittal plane data of the TD population's kinematic data, this offset was observed to be larger with the CP population. The offset is likely caused by a difference in segment definitions between the marker-based model they used and Theia3D's inverse kinematic approach. The TD pediatric population had larger RMSDs than what was observed in healthy adults (10, 55). They concluded that the markerless system must be improved before implementation in a pediatric clinical setting; however, data compared in the frontal and transverse planes of the knee that provided large RMSDs were not fairly compared as the study utilized the Human Body Model (HBM) for their marker-based system (55). The HBM does not calculate movement in the frontal or transverse planes of the knee due to modelling constraints. The data provided from HBM in those planes was a straight line which does not accurately reflect the motion occurring at the knee joint. Although this paper provides preliminary evidence of limited agreement in the ankle and hip it does not provide a full three-dimensional comparison of Theia3D to a marker-based system.

A full three-dimensional concurrent assessment of Theia3D and a marker-based motion capture system was completed with 36 clinical patients (2-25yrs old) with varying diagnoses (56). Root-mean-square deviations were calculated between the two systems for lower body kinematics, the frontal and transverse planes showed the greatest RMSDs, especially in the knee and hip where significant misalignment of the knee flexion-extension axis was observed. This misalignment was observed to cause an error in the calculation of hip rotation which is problematic for clinical implementation (56).

The literature suggests preliminary evidence for the concurrent validation of Theia3D; however, small sample sizes and marker-based model differences limit the conclusions that can be made regarding the appropriateness of Theia3D for pediatric clinical gait analysis.

2.5 Determining Validity

Validity is important for ensuring that a tool or instrument is accurately measuring the construct. There are five main types of validity: internal validity, external validity, construct validity, content validity, and criterion validity.

Internal validity aims to prove that the data is free from random error that can be caused by improper instrumentation or bias within the tested sample, while external validity aims to prove that the data is generalizable to a large population. Construct validity is known as the queen of all validity as it proves that the test correctly measures the concept it was designed to

(57). Content validity works to prove that the test or measure comprehensively addresses the area of interest while criterion validity tries to prove that the data gathered from one test strongly correlates to the data produced by another (57). One aspect of criterion validity is concurrent validity where two instruments measure the same construct at the same time, the two sets of data are compared to determine how related the two samples are. Generally, concurrent validity compares a new instrument to a 'gold standard'; however, when a gold standard does not exist, an understood and trusted instrument can be compared instead. There is a higher risk of error when there is no gold standard as the new instruments is being compared to one with known errors or limitations. Concurrently validating technologies before clinical implementation is important for understanding how the technology performs and what it measures compared to the technology already being used.

Validity can be thought of like an argument in a court of law. There is a certain level of evidence required to convince the jury beyond a reasonable doubt that something is true. The same level of evidence is required to convince the scientific community that a test, instrument, or measure, accurately measures what it states it does (58). There are several frameworks to guide researchers in designing research studies to validate tests. Kane's framework of validation utilizes a two-step approach where a claim is stated, evidence is gathered and evaluated, before the evidence is generalized for the population (58). Generalizing the evidence to the population should be done using careful language that first states the level of evidence that was assessed, addresses what the measure is assessing, and reports the population the measure of tested on. Kane suggests that evidence towards validity should never be communicated as a direct answer but instead as an inference towards what the measure could be accurate for (59).

2.5.1 Validation with Small Sample Sizes

When assessing the validity of a new technology for measuring gait outcomes, it is important to understand how differences within the population can change the data collected. In largely heterogeneous populations (i.e. individuals with cerebral palsy and children) it is recommended to have a representative number of participants per sub-group assessed —when validating technology for children, both the age of the child and the sex should be taken into account— therefore, large sample sizes with age and sex matching would be beneficial (60). Depending on the goal of the study and the study outcomes varying sample sizes and number of trials recorded per participant may change. Studies analyzing kinetic data (i.e. ground reaction forces) will require more participants and more trials to be recorded per participant to gather high-quality data than a study analyzing kinematics only (61). Many studies assessing the accuracy or repeatability of gait measurement systems use sample sizes of between 30 and 50 participants (12).

2.6 Summary

Children with cerebral palsy and other mobility impairments routinely complete 3D-GA to assess their walking mobility; however, the current marker-based methods can be intolerable for many children, thus limiting access to this important clinical tool. Markerless motion capture could decrease the patient burden of completing a 3D-GA; however, current literature focuses on a healthy adult population with only preliminary evidence for clinical use. Theia3D shows good concurrent validity and reliability in a normative adult population; however, more research is required for the determination of clinical implementation, especially in a pediatric population. Assessing the accuracy of Theia3D when used with pediatric populations with and without movement impairments is required prior to clinical implementation as children cannot be treated as tiny adults and it is important to understand the impact and usability of new technologies with children specifically.

Chapter 3: Comparing Marker-based and Markerless Motion Capture for Three-Dimensional Clinical Gait Analysis in Pediatric Populations with and without Mobility Impairments

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3.1 Abstract

Background: Marker-based motion capture is commonly used to collect three-dimensional kinematic data that informs clinical decision-making for children with cerebral palsy and other mobility impairments. Marker-based motion capture has many limitations (i.e. time-consuming, marker occlusions, inaccurate marker placements, tight clothing) that may make the collection of quality data challenging. Markerless motion capture technologies (Theia3D) that utilize computer vision to identify landmarks may mitigate some challenges while making the assessment more comfortable for pediatric populations with and without mobility impairments to complete assessments. Preliminary evidence of the concurrent validity of markerless motion capture compared to the marker-based standard has been conducted in adult populations, but there is limited evidence investigating its accuracy when used with pediatric populations.

Research Question: How does markerless motion capture compare to the marker-based standard for conducting clinical gait analysis in pediatric populations with and without mobility impairments?

Methods: Two cohorts (typically developing children and children with mobility impairments) completed a three-dimensional clinical gait assessment with the marker-based and markerless systems running concurrently. Root-mean-square deviations (RMSD) and mean absolute error (MAE) were assessed across 100% of the normalized gait cycle to determine the level of agreement between the two systems.

Results: Twenty-eight typically developing children (16 males/15 females; median (25th percentile, 75th percentile) age: 8 (5, 11) years; median height: 140 (119, 153) cm, median mass: 31(22, 42)) and 11 children with mobility impairments (9 males/2 females, age: 12 (9, 14) years, height: 162 (130, 172) cm, mass: 52 (27, 55) kg, underlying diagnosis: cerebral palsy-9, rare genetic condition-1, and musculoskeletal condition impacting gait-1) participated in the study. Kinematic waveforms in the markerless system were similar to those of the marker-based; however, systematic offsets were observed in the frontal and transverse planes with the markerless system. Median RMSDs and MAEs for both cohorts were <6º in all joints except for the transverse plane of the hip and knee.

Significance: This study presents good evidence that markerless motion capture is accurate for assessing kinematic data in the sagittal and frontal planes for children with and without mobility impairments. Good agreement was observed in all joints except the transverse plane of the hip and knee. This disagreement in the transverse plane is a limitation to clinical implementation as such data often informs clinical decision-making. Markerless motion capture is appropriate for use with typically developing populations or for children with mobility impairments only when the clinical question does not require the analyses of joint rotations and is best utilized for questions exploring motion in the sagittal plane.

3.2 Introduction

Motion capture is a useful tool for biomechanical analysis and is often used to conduct clinical gait assessments for children with cerebral palsy and other mobility impairments. The quantitative data gathered during such a clinical gait analysis is often used to inform clinical decision-making (1, 2, 62). Marker-based motion capture is the current clinical standard and utilizes reflective markers placed on bony landmarks to track lower limb joint motion. The use of reflective markers on bony landmarks has several disadvantages, especially when used with pediatric populations: they require a lengthy set-up where an expert palpates bony landmarks and places the reflective markers, bony landmarks must be physically accessible (potentially requiring the patients to wear tight fitting or revealing clothing), and the slight misplacement or movement of a marker can have a large impact on data quality (63). When conducting marker-based motion capture with pediatric populations the size of the markers can also make it challenging to accurately place them on the bony landmarks, and for children with anatomical differences, finding the bony landmarks can be very time-consuming. When conducting a marker-based assessment with children who walk with the assistance of a gait aid (such as an anterior walker) it can be challenging to gather accurate data as the markers can be blocked by the walking aid (45). In recent years, deep learning algorithms and computer vision have become increasingly common for biomechanical analyses (64, 65). Using these markerless technologies for clinical gait assessments could decrease some of the limitations observed when working with pediatric populations.

Theia3D (Theia Markerless, Kingston, ON) is a markerless motion capture technology that utilizes computer vision to identify salient features of the human body in each frame of a recorded video. The validity of Theia3D compared to a marker-based system when used with a healthy adult population has been demonstrated (10). Theia3D was shown to produce spatiotemporal parameters consistent with those seen in marker-based systems (11), and to demonstrate good inter-session repeatability for kinematic measures in a healthy adult population (17) and in those with knee osteoarthritis (51). Preliminary evidence supports the validation of Theia3D compared to the Plug-in-Gait model (56) and the Human Body model (10) when used with children and adolescents with cerebral palsy. To our knowledge, there is no literature investigating the concurrent validity of Theia3D against the Helen Hayes model (66) for pediatric populations with or without mobility impairments.

3.3 Methods

The dual cohort study assessing the concurrent validity of a markerless motion capture system for two distinct pediatric populations was approved by the Conjoint Health Research Ethics Board at the University of Calgary (REB22-1481) and was conducted at the Alberta Children's Hospital's Movement Assessment Centre.

3.3.1 Participants

This study involved two distinct cohorts. We recruited a convenience sample of 30 typically developing children using the Healthy Infants and Children's Clinical Research Program (HICCUP (67)), a population-based database of children interested in participating in clinical research, the sample size was informed by the number of clinical cases the Movement Assessment Centre (MAC) conducts annually. The inclusion criteria for this cohort required participants to be healthy by self-report. Exclusion criteria were self-reported lower body musculoskeletal injury or concussion occurring within the last six months or diagnosis of a neuromotor impairment that could impact typical gait. The clinical cohort consisted of 11 patients recruited from the MAC at the Alberta Children's Hospital during their clinically referred marker-based three-dimensional gait assessment. There were no set exclusion criteria as we aimed to collect a sample representative of those who were referred for clinical gait assessment. Written informed consent and/or assent was collected from the participants and or/their parents or guardians where applicable.

3.3.2 Data Collection

All participants ambulated across a walkway (4.2m x 10m) fitted with four force plates (AMTI six-channel; AMTI, Watertown, MA) and surrounded by cameras for both a marker-based and markerless system (see Appendix B, Figure B.1). Participants in the typically developing cohort completed eight passes of the walkway unassisted. Participants in the clinical cohort completed at least two passes of the walkway independently or with the assistance of a gait aid (anterior or posterior walker). The clinical assessments frequently contained multiple walking conditions (while wearing ankle-foot orthoses vs barefoot); however, only the barefoot walking condition will be presented here.

Participants recruited for the clinical cohort provided their Gross Motor Classification System (GMFCS) level, Gillette Functional Assessment Questionnaire (FAQ-10) score, and their Functional Mobility Scale (FMS) to describe their level of ambulation.

3.3.2.1 Motion Capture Equipment

The two motion capture systems were run asynchronously but were controlled using a single button press, coded to start and end the recordings of each trial from each system at approximately the same time.

3.3.2.1.1 Marker-based System

The marker-based system consisted of 12 Eagle4 infrared cameras recording at 120Hz. The cameras were wand-calibrated, when necessary (around once a month or when a camera was touched), with the data collection area focussing on the force plates embedded in the walkway. EVaRT (Motion Analysis, Rohnert Park, CA) simultaneously collected data from the synchronized infrared cameras and force plates. Marker tracking for the static and dynamic trials was completed in EVaRT following the modified Helen Hayes marker model (66).

3.3.2.1.2 Markerless System

The markerless system consisted of eight synchronized commercial-grade video cameras (Sony DSC-RX0M2) recording at 119.8Hz. Videos were downloaded from the cameras and uploaded to Theia3D (Theia Markerless Inc., Kingston, ON. V023.1.0.3161) for further processing.

3.3.3 Data Extraction and Analysis

Tracked marker trials were exported as c3d files for further extraction for the marker-based system and Theia3D was used to identify the landmarks and create a 4x4 pose matrix for each trial collected (Figure 3.1).

Data was extracted from each system using their independent software. The markerless videos were initially processed on Theia3D where a 3D model within the pose matrix file of each trial, this model is automatically rendered when the file is uploaded to Visual3D (HAS-Motion Inc. Kingston, ON) for further processing. The marker-based pipeline required the creation of a custom model that was applied to each participant's static trial and used for further processing in Visual3D. We constrained the hip, knee and ankle joints to three degrees of freedom and visually identified the frame corresponding to initial contact for each system independently. For the marker-based data the synchronized force plates were used to determine the frame where initial contact occurred while the markerless videos were visually inspected. Following the calculation of joint angles within Visual3D and the determination of gait events in their respective software all trials were normalized to 100% of the gait cycle using a custom MATLAB (MathWorks, Natick, MA, v2023b) script and applied an 8Hz low-pass Butterworth filter to smooth the waveform.

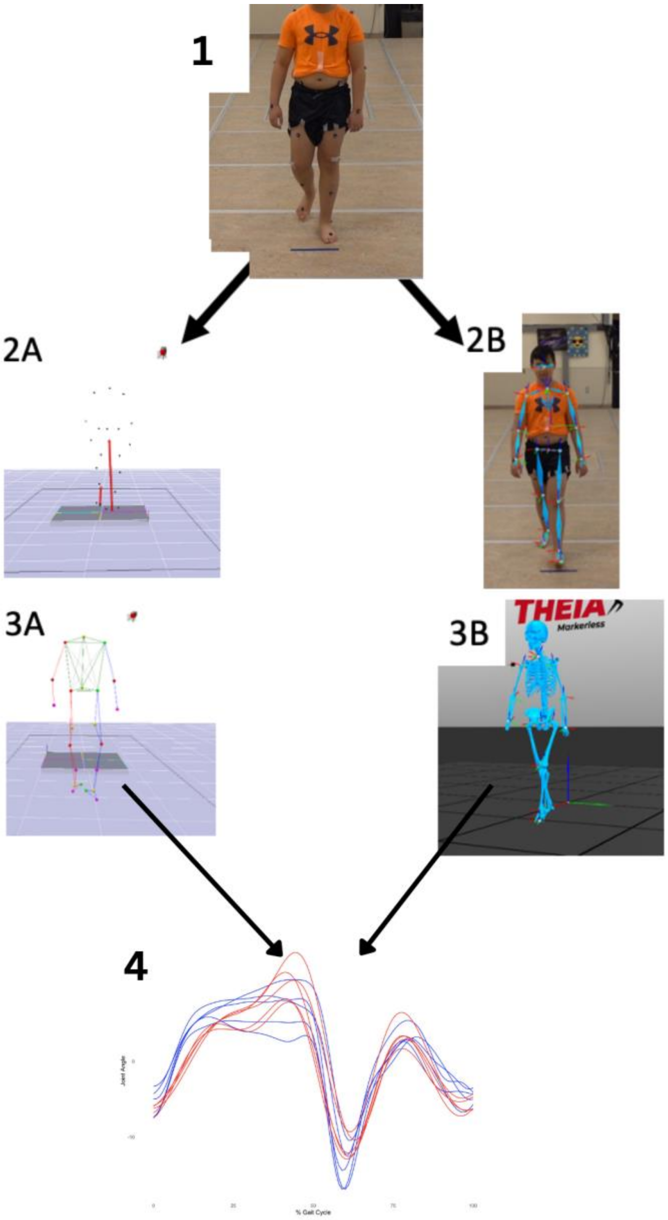

Figure 3.1 *Concurrent motion capture (marker-based and markerless) data collection and processing pipeline. 1) The data collection task was completed with both systems running concurrently. 2A & 3A) Marker-based extraction started in EVART where markers were tracked. 2B & 3B) Markerless videos*

were processed in Theia3D where the skeletal model and 4x4 pose matrix were created. 4) Post-processing of the waveforms from each system were superimposed for comparison.

3.3.4 Statistical Analysis

Concurrent validity was investigated using root-mean-square deviations (RMSDs) and mean absolute error (MAEs) calculated across 100% of the normalized gait cycle. RMSDs measure the prediction error between two models by taking the square root of the averaged square error; however, RMSDs are sensitive to outliers as large errors will cause the RMSDs to skew higher than the true error. MAEs are a measure of between the two observations and are not as sensitive to large differences in the data. Assessing the validity of Theia3D requires a comparison against the current standard; therefore, the predicted values are reflected in the marker-based data while the markerless is represented by the observed values. Data was analyzed using R (R version 2024.04.02+764). RMSD and MAE were reported as median (25th percentile, 75th percentile) unless otherwise specified. Agreement between the two systems for the typically developing cohort was examined through the means of five strides per side of the body for each participant. The clinical cohort utilized the greatest number of strides available per side in the barefoot condition. While gait events were identified independently, the same strides were used for both systems. To compare the two systems, waveforms for the hip, knee, and ankle are represented; however, limitations to the marker-based foot model used prevented statistical comparison of the ankle joint in the frontal and transverse planes.

The reliability of marker-based motion capture systems is well established. The expected error in marker-based systems is a MAE of less than five degrees in the sagittal plane and two degrees or less in the frontal plane (13).The error of marker-based systems was used to determine the acceptable difference between the marker-based and markerless systems.

3.4 Results

3.4.1 Participants

Twenty-eight typically developing children (16 males/ 15 females, median (25th percentile, 75th percentile) age: 8 (5, 11) years, height: 140(119, 153) cm, mass: 31(22, 42)) and 11 clinical participants (9 males/ 2 females, age: 12(9, 14) years, height: 162(130, 172) cm, mass: 52(27, 55) kg) completed the study. Diagnoses and ambulatory ability (Figure 3.2) for the clinical population varied. Nine participants had cerebral palsy, one had a rare genetic condition causing spasticity and one had an anatomical difference impacting gait.

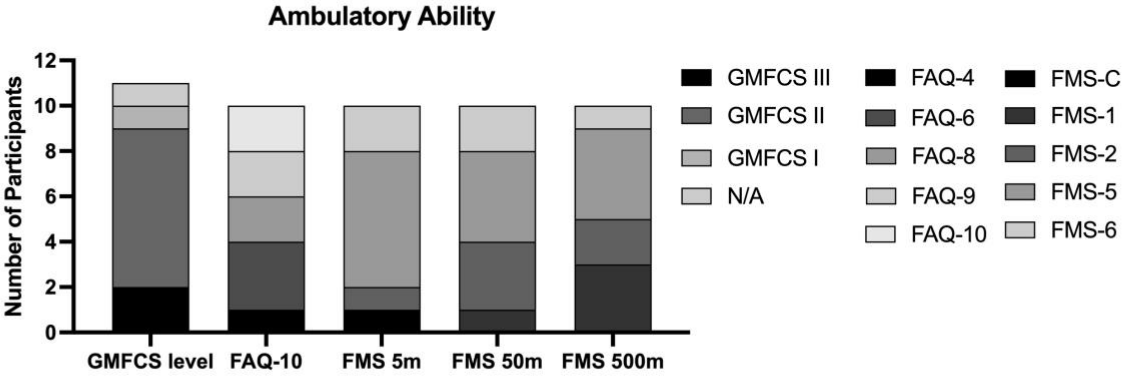

Figure 3.2 *Graphical representation of ambulatory ability of the clinical cohort (n=11). Abbreviations: GMFCS: Gross Motor Function Classification System; FAQ: Functional Assessment Questionnaire; FMS: Functional Mobility Scale.*

3.4.2 Typically Developing Cohort

Figure 3.3 illustrates the kinematic waveform comparisons between the marker-based and markerless systems for a representative participant (see Appendix E, Figure E.1 for right leg waveforms). The waveforms have consistent shapes between systems in the sagittal plane, while the waveforms showed greater variation in the frontal and transverse planes. Systematic differences were observed in the frontal and transverse planes, systematic differences may be caused by segmental definition or modelling differences between the two systems.

There were no significant differences between the RMSDs or MAEs in the left and right sides of the body; therefore, only data from the left side is presented here (see Appendix D for right side data). The greatest agreement between the marker-based and markerless systems was observed in the sagittal plane of the ankle with a median RMSD 2.6º (2.0º, 3.6º) and a MAE of 2.1º (1.7º, 3.3º). The sagittal plane of the ankle had the smallest error range (4.1º) with the minimum MAE observed being 1.0º and the largest 4.1º. The sagittal and frontal planes of the knee had relatively good agreement with median RMSDs of 3.9º (3.2º, 6.0º) and 2.9º (2.2º, 3.4º) respectively. The greatest deviation between the two systems was observed in the transverse plane of the knee with a median RMSD of 16.3º (10.9º, 20.9º). The largest range of MAE was observed in the transverse plane of the knee with a 26.1º range across the typically developing cohort. The best agreement at the transverse knee had a mean absolute error of 4.5º, while the greatest MAE was 30.7º. Differences in the transverse plane of the hip were not as large as those observed in the knee with a median RMSD of 5.9º (4.0º, 9.2º) and a median MAE of 5.2º (3.4º, 8.4º). Figure 3.4 displays the measures of concurrent validity for all participants across all joints and planes for the left side (see Appendix D, Figure D.1 for right leg).

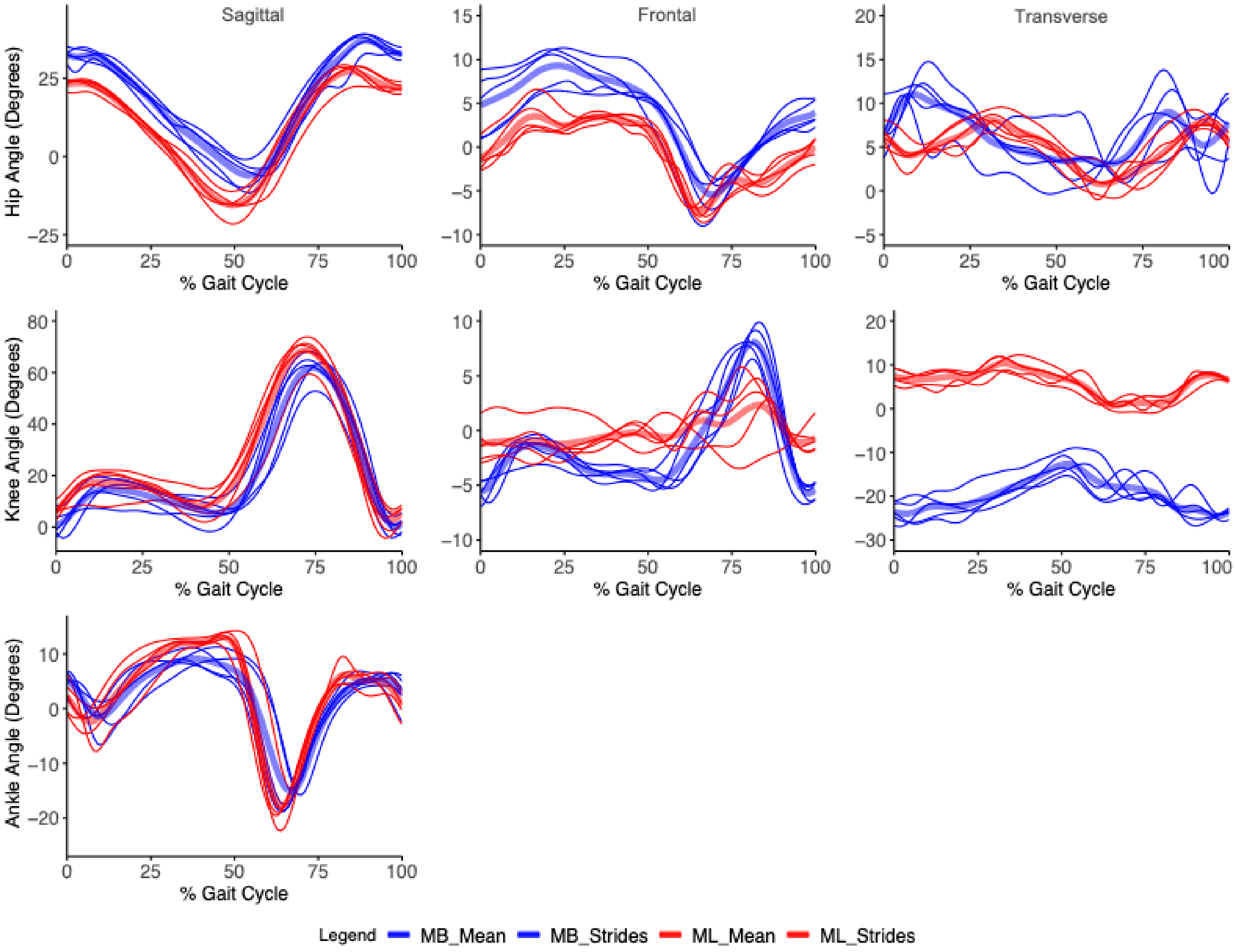

Figure 3.3 *Representative kinematic waveforms between systems (marker-based and markerless) for the left hip, knee, and ankle of a five-year-old typically developing female (n=1). Thin blue lines represent strides collected using the marker-based system while the thicker and more transparent blue band represents the mean of the marker-based strides. Red lines represent strides collected using the markerless system while the more transparent red band represents the mean of the markerless strides.*

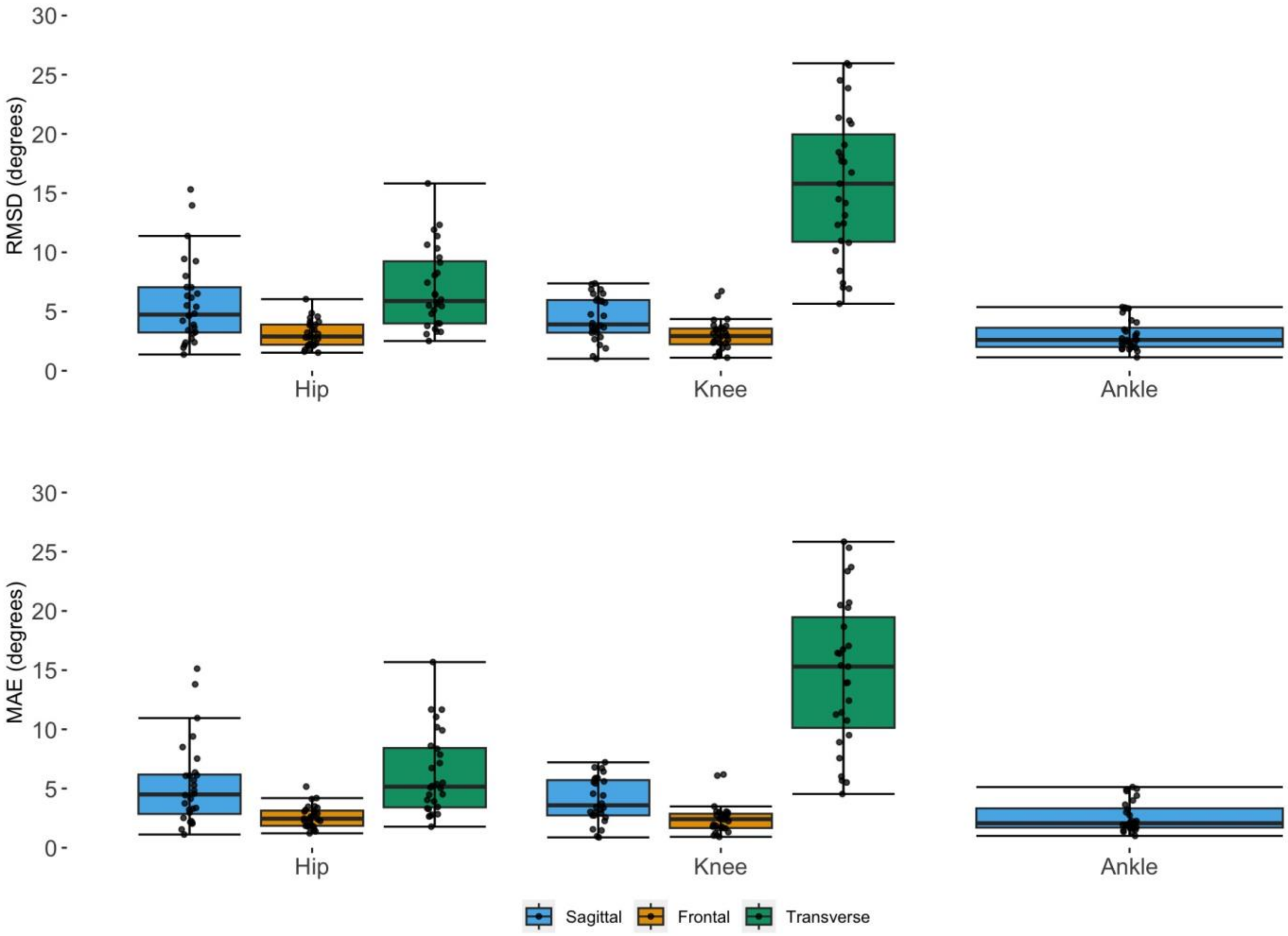

Figure 3.4 *Boxplots representing sample statistics of the typically developing cohort (n=28) for root-mean-square deviations and mean absolute error between the marker-based and markerless systems for the left side of the body. Top: RMSD analysis for the marker-based versus markerless system. Bottom: MAE analysis for the marker-based versus the markerless systems.*

3.4.3 Clinical Population

Kinematic waveforms from both systems generally followed the same shape with greater variability observed in the transverse plane as shown for a representative participant in Figure 3.5 (see Appendix E, Figure E.2 for right leg). As the participant has significant mobility impairments the waveforms do not follow the shapes of typical gait.

Figure 3.6 illustrates the level of agreement in the entire clinical cohort. The best agreement was observed in the sagittal plane of the right hip with a median RMSD 3.0º(2.2º, 8.4º) and a median MAE of 2.8º(1.9º, 8.0º) while the largest mean absolute error was observed in the transverse plane of the left knee with a median MAE of 15.1º(6.8º, 20.6º) the right knee was not much better with a median MAE of 8.4º(7.9º, 32.4º) (see Appendix D, Figure D.2 for right leg). The greatest range in mean absolute error was observed in the transverse plane of the right knee with a range of 54.2º. The minimum error identified in this plane and joint was 4.7º while the highest MAE was 58.8º. The maximum MAE detected was observed in a participant who had high variability between trials and a large offset between the two systems. Adjusting for the systematic offset would likely decrease the size of the error.

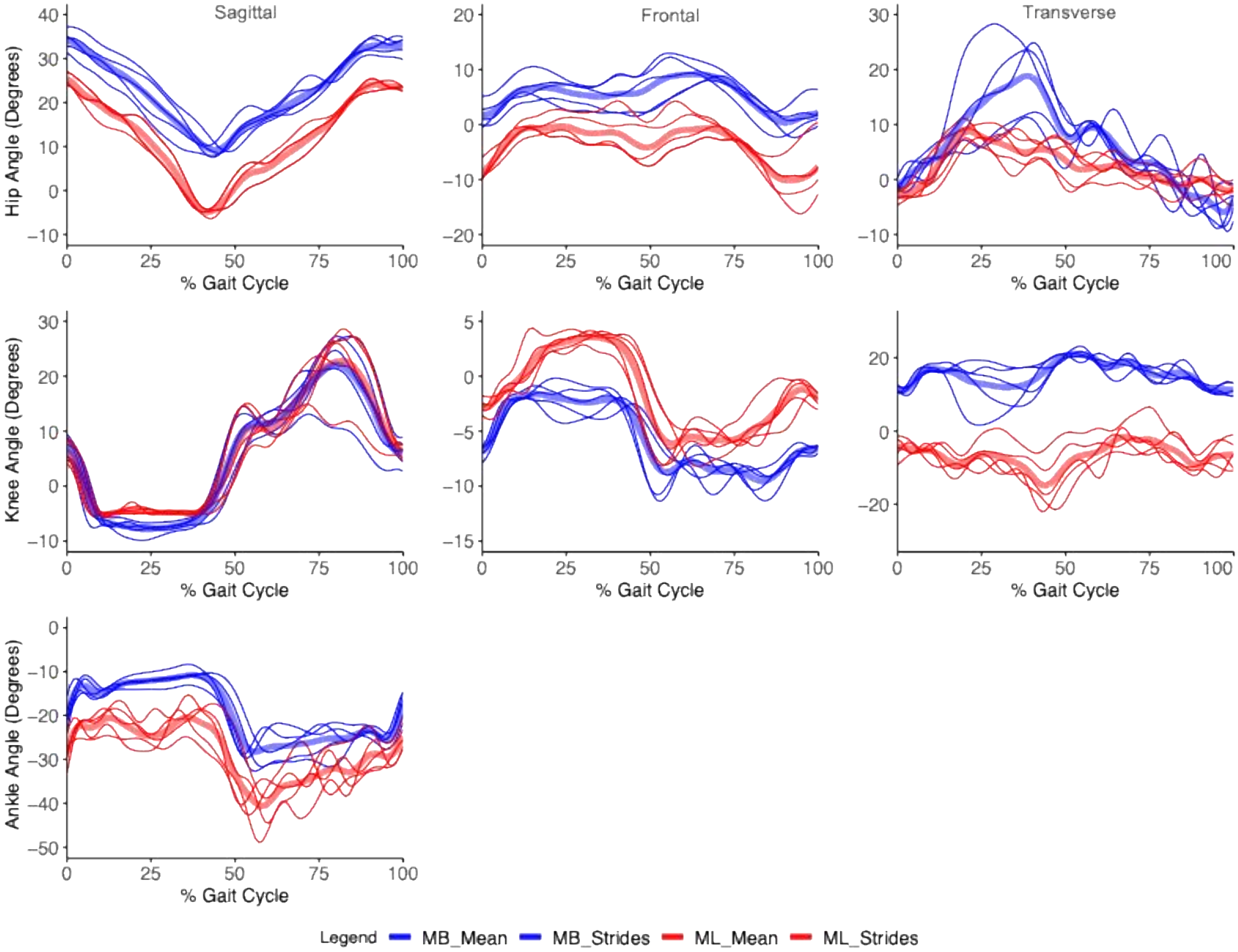

Figure 3.5 *Representative kinematic waveforms between systems (marker-based and markerless) for the left hip, knee, and ankle of a ten-year-old male with cerebral palsy (n=1). Thin blue lines represent strides collected using the marker-based system while the thicker and more transparent blue band represents the mean of the marker-based strides. Red lines represent strides collected using the markerless system while the more transparent red band represents the mean of the markerless strides.*

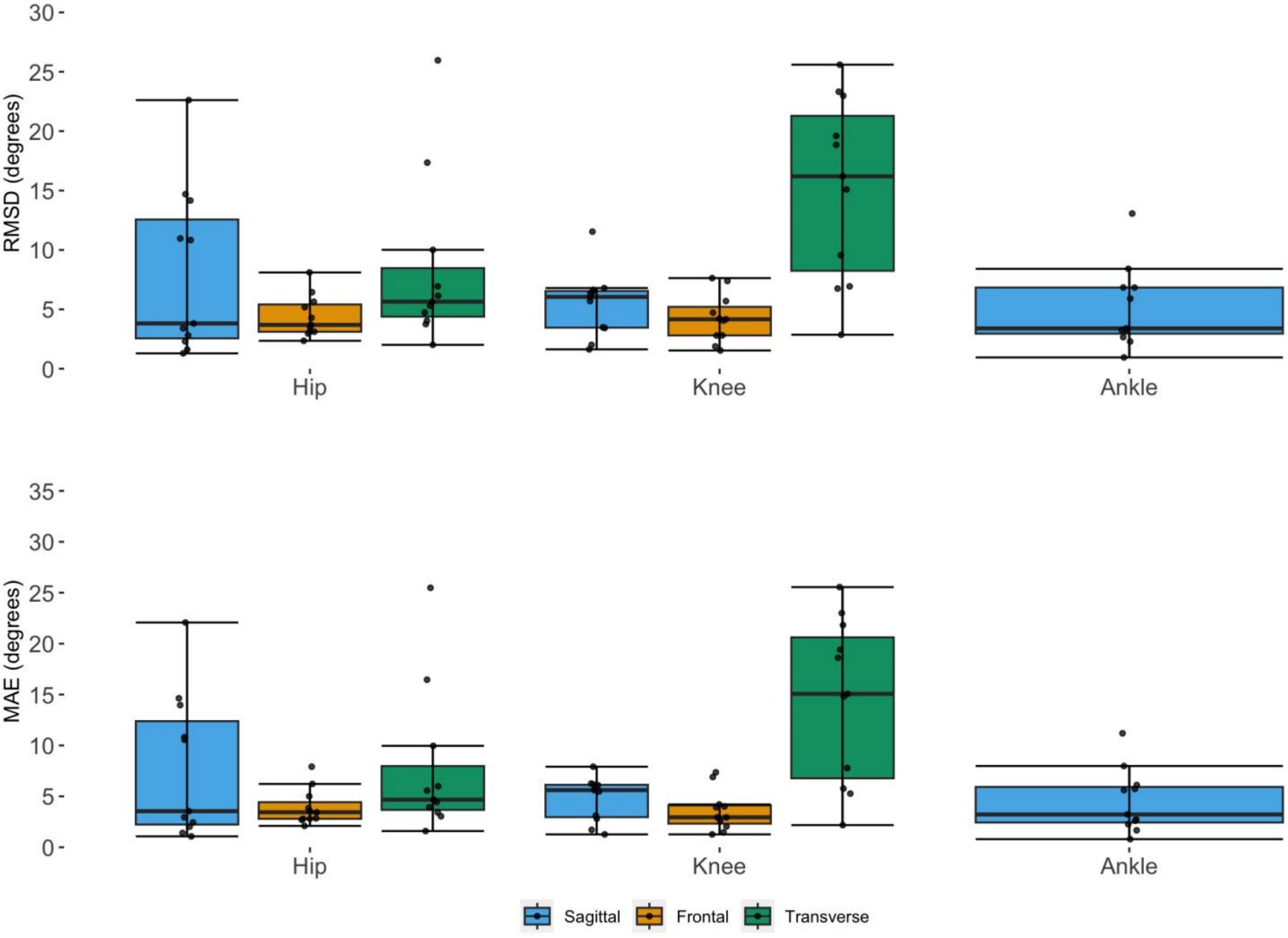

Figure 3.6 *Boxplots representing sample statistics of the clinical cohort (n=11) for root-mean-square deviations and mean absolute error between the marker-based and markerless systems. Top: RMSD analysis, Bottom: MAE analysis between the two systems.*

3.5 Discussion

Kinematic waveforms between the marker-based and markerless systems showed similar patterns with median RMSD and MAE both less than six degrees in the sagittal and frontal planes for all joints. The transverse plane had the greatest differences between systems with RMSDs as large as 58.9º. Differences in the kinematics are likely explained by differences in the segment definitions in the models applied. The largest RMSDs were observed in the transverse plane for both the typically developing and the clinical cohort, this observation is consistent with the literature where large RMSDs in the transverse plane of the hip, knee, and ankle were observed (54). One study attempted to adjust for modelling differences found in the static pelvis by applying an offset calculation, this adjustment improved the agreement between the marker-based and markerless systems (56). There are a few advantages to not correcting for the offset in the frontal and transverse planes: 1) visualizing and understanding the impact of the different segment definitions is important for predicting how the data may differ when markerless systems are used and 2) prior to implementing markerless systems clinically, it is important to understand segmental definition and model differences to ensure that data analyzed in the future is comparable with that collected throughout the patient's history.

Interestingly, the marker-based system limited the data that could be collected for this study. Of the initial 31 participants recruited, three participants were excluded from the final analysis due to issues in their marker data. One participant had excess adiposity making accurate marker placement challenging. Adiposity covered some markers while others became tilted due to skin movement during walking. The markerless data collected for this participant was comparable to the other participants. A second participant was excluded for walking outside of the calibrated range. The marker-based system has a relatively small collection area that consists only of the middle region of the walkway (see Appendix B) while the markerless area will collect data anywhere in the room that is visualized by the video cameras (the quality of data collected outside of the calibration range was not tested). This participant's markerless data looked typical, while their marker-based data had frequent marker drop-out that increased the amount of interpolation required. The third participant was excluded for having too much movement during the static trial. The loss of a quality static trial resulted in data that had abnormal ranges and shapes, and there was an increase in crosstalk between the sagittal and frontal planes of the knee and hip, leading to waveforms in the frontal plane following the typical sagittal plane shape. Clinical gait labs would ensure that data is collected as seamlessly as possible and would repeat collections to ensure enough data is collected to answer the clinical question. However, when working with young children, those who may not have the cognitive capacity to follow instructions, or with those who fatigue quickly, there is an increased risk of data loss or poor-quality data when marker-based systems are used.

Clinically, the frontal and transverse planes of the ankle are not analyzed. Instead, the foot progression angle or foot rotation is typically assessed (56). The current marker-based systems are limited in their ability to understand how the foot and ankle move, especially in children with small feet or children who have anatomical differences that impact their feet, as these individuals may not have enough room on their foot to place the markers required for more complicated foot models. Ankle waveforms for the frontal and transverse planes were not addressed in this study as the Helen Hayes marker model assumes the foot is a rigid body and uses a very minimal foot model. The markerless data for these planes was highly variable but centred around zero degrees while the marker-based data had two distinct patterns, one pattern was similar in shape but not magnitude to the sagittal plane while the other patterns centred around zero degrees similar to the markerless data. No comparison could be made for these planes at the ankle as the lack of a true gold standard does not allow us to determine which of the systems is more correct.

Markerless motion capture may not have the level of sensitivity required to address complicated clinical questions or those examining joint rotations. However, the level of agreement between the two systems in the sagittal plane is a promising result for future implementation in clinical settings as markerless systems could provide a less burdensome 3D gait assessment.

3.5.1 Limitations

A limitation of this study is the relatively small clinical sample, a larger study with more participants and greater clinical diversity is required to truly determine the concurrent validity of markerless motion capture for pediatric populations and to better understand the bounds of the markerless technology as it may not be appropriate for all clinical questions or for use with certain diagnoses as the algorithm is not likely trained on individuals with complex or differing anatomy. Future research should work to build a set of guidelines around which clinical populations and questions markerless motion capture is valid for exploring, including the impact of wearing ankle foot orthoses (AFO) and the use of larger walking aids as those are known limitations to the current standard marker-based systems.

3.6 Conclusion

This study, combined with the literature provides good evidence that markerless motion capture is accurate for assessing lower-body kinematics in the sagittal plane for children with and without mobility impairments. Kinematic waveforms calculated using markerless motion capture show good alignment with the marker-based standard in the sagittal and frontal planes when used with typically developing pediatric populations. Waveforms are similar in both systems for children with cerebral palsy and other mobility impairments; however, larger differences and systematic offsets are observed. Larger studies are needed prior to clinical implementation and sensitivity in the transverse plane needs to increase before the system can be used to inform clinical decision-making for children with cerebral palsy.

3.7 Contribution of Authors

The authors confirm contribution to the thesis document and the manuscripts it contains as follows: study conception and design: Amanda Rande, Ion Robu, Gina Ursulak, Gregor Kuntze, Elise Laende, Jereme Outerleys, Ranita H.K. Manocha, Rubini Pathy, Elizabeth G. Condliffe; data collection: Amanda Rande, Mahika Sharma, Ion Robu, Gina Ursulak, Amanda Beaudin; analysis and interpretation of results: Amanda Rande, Mahika Sharma, Ion Robu, Elizabeth G. Condliffe; draft manuscript preparation; Amanda Rande, Elizabeth G. Condliffe. Co-authors have not had the chance to review the final manuscript.

3.8 Acknowledgments

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Chapter 4: What Not to Wear: Examining the usability of markerless motion capture for pediatric populations

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4.1 Abstract

Background: Three-dimensional gait analysis is important for informing the clinical care of children with mobility impairments. However, the current gold standard marker-based approach requires children to wear tight clothing and requires a lengthy marker placement process, which may be uncomfortable for children and adolescents. Markerless approaches may enable participants to wear clothing they are more comfortable in during the assessment while decreasing the time it takes to complete an assessment.

Research Questions:

- What is the usability of markerless motion capture methods for children completing 3D gait assessments?
- Does clothing impact the kinematic data gathering during a markerless assessment?
- What are the participants' perceptions of marker-based and markerless approaches to 3D gait assessments?
- Does a markerless approach decrease the time required to complete a 3D gait assessment?

Methods: In this cross-sectional study, participants completed two distinct 3D gait assessment protocols where the child wore either a) Conventional clothing (a shirt rolled up and shorts with the waistband rolled down to reveal the anterior superior iliac crests (location of pelvis marker when a marker-based system is used)) —referred to as the Conventional condition—, or b) unrestricted Street clothing —referred to as the Street condition. Root-mean-square deviations (RMSD) and an outlier analysis (Inter-quartile range (IQR) method) were used to determine the

impact of clothing on the kinematic data, RMSDs are reported as median (25th percentile, 75th percentile). Participants and their caregivers completed questionnaires investigating their perceptions of the Conventional and Street conditions. Proportions were used to explore the participants' perceptions of 3D- gait assessments and a Wilcoxon Signed Rank test ($\alpha = 0.05$) determined the significance of the time difference required to complete the Street versus Conventional conditions.

Results: Thirty typically developing children (15 males/ 15 females, mean (SD) age: 8.6 (3.48) years) completed the study. Median RMSDs were below 4° for all joints in all three planes of movement for all joints suggesting that most clothing has minimal impact on gait data. However, clothing should be form-fitting and pants should end above the ankle to ensure quality data is collected as outliers occurred in data collected with other clothing. Eighty percent of participants were willing to repeat the Street condition while only 28% would repeat the Conventional condition. Completing the Street condition was significantly faster than the Conventional condition ($p < 0.001$) with a difference of 11 minutes (9 min, 13 min).

Significance: Markerless systems may increase the usability of 3D gait assessments as participants can wear clothing, they are more comfortable in without adversely impacting the kinematic results. As this condition was also associated with perceived benefits from both the children and their caregivers as well as time-savings, markerless systems will likely improve the patient experience of 3D gait assessment.

4.2 Introduction

Three-dimensional gait analysis (3D-GA) is an important component of informing clinical decision-making and assessing the impact of therapeutic interventions for children with cerebral palsy and other mobility impairments (1-4). Traditional marker-based motion capture methods require the accurate placement of reflective markers on bony landmarks, which may require the patient to stand for prolonged periods and to wear tight or minimal clothing for marker placement (49, 62). For individuals with sensory sensitivities or those uncomfortable wearing the required clothing, the marker-based method may create an unpleasant experience or limit access to 3D-GA. Markerless motion capture technologies utilize computer vision to identify anatomical landmarks without reflective markers (66). In healthy adults and for those with knee osteoarthritis, a commercial markerless approach (Theia3D, Theia Markerless Inc., Kingston, ON, v2024.02.2) has shown good inter-session repeatability(17), low inter-session variability (17, 51), and good reliability when athleisure-style clothing is worn (52). Preliminary evidence supports the concurrent validity of markerless 3D-GA in a clinical population of children and young adults (56, 68); however, no studies have investigated the usability of markerless systems in pediatric populations, despite many —15% of gait labs in Europe only assess children and 59% of lab assess both children and adults (49)— clinical gait labs assessing children. The factors impacting the usability of markerless 3D-GA including the diversity of clothing that is (and is not) appropriate have not been systematically studied.

It is important to determine the impacts of clothing options on kinematics and participant perceptions of 3D-GA before clinical implementation. This study evaluates the usability of markerless motion capture technology for gait analysis in a typically developing pediatric population. Specifically, we assess three aspects of usability compared to the conventional marker-based method. Firstly, we evaluate the impact of unconstrained clothing on joint kinematics. Secondly, we explore participants' perceptions of the two approaches to 3D-GA. Lastly, we compare the time required to conduct 3D-GA using each approach.

4.3 Methods

This cross-sectional study investigating the usability of a markerless motion capture system for a pediatric population was approved by the Conjoint Health Research Ethics Board at the University of Calgary (REB22-1481). The study was conducted at the Alberta Children's Hospital's Movement Assessment Centre (MAC).

4.3.1 Participants

A convenience sample of 30 typically developing children (aged 4 to 17) were recruited using the Healthy Infants and Children's Clinical Research Program (HICCUP [50]) a local population-based database of children and families who have consented to be contacted for medical research. The inclusion criteria for this study required participants to be healthy by self-report. Exclusion criteria were self-reported lower body musculoskeletal injury, concussion —occurring within the last six months—, or diagnosis of a neuromotor impairment that could impact typical gait. Written informed consent and/or assent was collected from the participants and/or their parents or guardians where applicable.

4.3.2 Data Collection

Participants completed two gait assessments in a single visit: a) Conventional Condition: this mimicked the traditional marker-based assessment, where participants wore shorts and a t-shirt taped up to expose their bony landmarks and had markers applied to these landmarks; b) Street Condition: participants wore the clothing they arrived in (i.e. this condition was unconstrained). Participants were required to remove their shoes and asked to remove their socks in both conditions. The order of condition completed was block randomized using a random number generator with 2 blocks (males and females) with equal sex distribution assigned to each order. Each participant ambulated eight lengths of a raised walkway (4.2m x 10m) at a self-selected pace. Eight video cameras (Sony DSC-RX0M2) surrounded the walkway, and videos were recorded at 119.8 Hz. Cameras were calibrated at the start of each data collection day using a custom checkerboard.

4.3.2.1 Participant and Caregiver Perceptions

Participants and their caregivers completed a short questionnaire after the gait assessments were completed (see Appendix H). Participants with difficulty reading or writing were helped by their caregivers or a member of the research team. Caregivers with multiple children participating in the study only completed the questionnaire once. Participants were asked to rate how they felt during each assessment using the Five Degrees of Happiness Smiley Face Likert Scale (69). They were asked which assessment they preferred with the option to write an explanation. Caregivers were asked if the walking during the assessment was typical of that participant's walking.

4.3.2.2 Assessment Time

The time each assessment began and ended was recorded on the data collection sheet by a member of the research team. The Conventional condition encompassed the time for the participant to change into the required clothing, placement of reflective markers, recording of a static trial, recording of eight walking trials, removal of the markers, and the participant changing back into their original clothing. The Street condition encompassed the time for the participant to remove their shoes and socks, the recording of eight walking trials, and the participant re-donning their shoes and socks.

4.3.3 Data Analysis

Theia3D (Theia Markerless Inc., Kingston, ON) and Visual3D (HAS-Motion Inc., Kingston, ON), were used to define and calculate joint angles. We constrained the hip, knee and ankle joints to three degrees of freedom and visually identified the frame corresponding to initial contact. We applied an 8Hz low-pass Butterworth filter and normalized joint kinematics to 100% of the gait cycle with a custom script in MATLAB (Mathworks, Natick, MA, v2023b).

For each participant in each condition, we calculated the mean joint angle in the sagittal, frontal and transverse planes at the hip, knee and ankle from six strides per side. We used root-mean-square deviation (RMSD) to determine the agreement between the two conditions. We defined outliers as data outside the bounds determined using the interquartile range (IQR) method. The lower limit was calculated as the 25th percentile minus 1.5 times the IQR and the upper limit was calculated as the 75th percentile plus 1.5 times the IQR (70).

4.3.4 Statistical Analysis

Data was analyzed using R (R version 2024.04.2+764). Kinematic and time data descriptive statistics are presented as median (25th percentile, 75th percentile). Questionnaire data was analyzed in SPSS (SPSS Inc., Chicago, Illinois) with proportions representing the participant and caregiver responses. A Wilcoxon Signed Rank test with a significance level of 0.05 was used to determine the statistical significance of the time difference.

4.4 Results

4.4.1 Participants

Thirty typically developing children (15 males/15 females, mean (SD) age: 8.6 (3.5) years, height: 136 (21.7) cm, mass: 34.3 (15.3) kg) completed both gait assessments, the clothing worn in each condition is shown in Figure 4.1. Twenty-six participants and 18 caregivers completed the perceptions questionnaire although not all participants completed all questions.

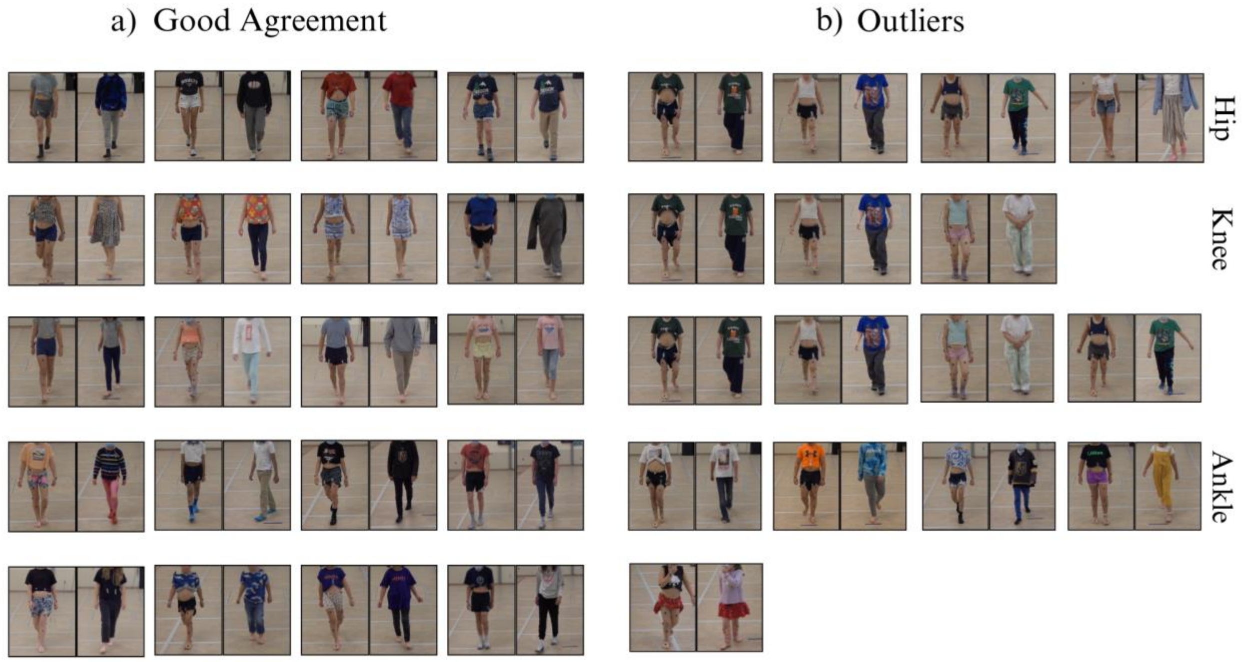


Figure 4.1 *Participant clothing worn during the conventional and street conditions. Images of participants' clothing worn in the Conventional (left box) and Street (right box) conditions are displayed. Participants are divided into (a) those who had a statistical agreement between conditions within the expected bounds in all planes for all joints on both sides and (b) those who had a kinematic outlier in at least one plane of one joint.*

4.4.2 Impact of Clothing Condition on Joint Kinematics

The Conventional and Street clothing conditions across the normalized gait cycle showed good agreement in all three planes of motion at the hip, knee and ankle (Figure 4.2, see Appendix F, Figure F.1 for right side). Median root-mean-square deviation (RMSD) across all joints and planes were below 4º (Figure 4.2); however, in the frontal and transverse planes, this represented a considerable proportion of the total motion (Table 4.1).

Clothing that contributed to differences in kinematics that were statistical outliers are displayed in Figure 1b. Twenty participants had good agreement between conditions in all planes for all joints on both sides. Outliers occurred in at least one plane for at least one joint for 10 participants. Four of those participants had outliers in more than one joint.

Common features of clothing observed in the outlier group were baggy clothing, shirts that extended below the hips, pants that extended past their ankle joint centre or pants that were similar in colour to their foot or the lab floor. Interestingly some participants whose kinematics were not outliers wore clothing with these features too (e.g. participant in row 2 column 4 of Fig 4.1).

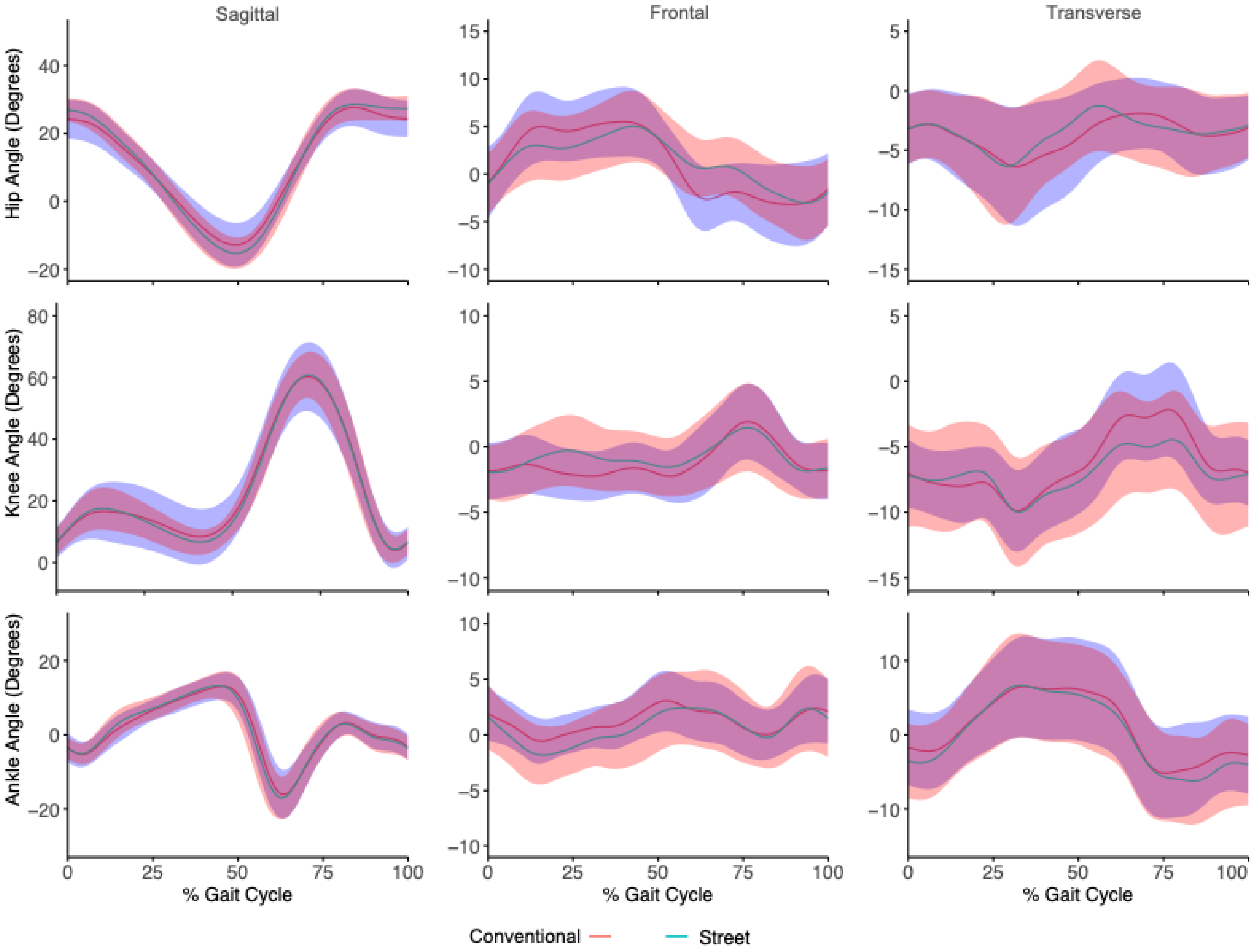


Figure 4.2 *Kinematic waveforms (left side) comparing the conventional and street clothing conditions for all participants (n=30). Solid lines represent the mean waveforms for the Conventional (blue) and Street (red) clothing conditions across all participants. The shaded bands represent +/- 1 standard deviation around the mean.*

Table 4.1 *Median root-mean-square deviation compared to the mean range of motion in each joint and plane*

Joint	Plane	Side	Median RMSD	Mean ROM	% of ROM
Hip	Sagittal	Right	3.4	42.1	8.2%
		Left	3.4	42.1	8.0%
	Frontal	Right	2.5	9.6	26.3%
		Left	2.5	8.4	30.1%
	Transverse	Right	1.8	5.0	34.9%
		Left	1.9	4.8	39.8%
Knee	Sagittal	Right	3.5	57.4	6.1%
		Left	3.8	56.5	6.7%
	Frontal	Right	1.7	4.0	41.5%
		Left	1.7	4.0	43.5%
	Transverse	Right	3.1	4.6	67.9%
		Left	2.8	6.6	42.2%
Ankle	Sagittal	Right	2.5	30.1	8.3%
		Left	2.5	29.8	8.4%
	Frontal	Right	1.4	6.4	21.7%
		Left	1.7	3.9	43.4%
	Transverse	Right	2.8	15.8	17.7%
		Left	2.6	12.3	20.8%

Abbreviations: ROM (Range of Motion); RMSD (Root-Mean-Square Deviation)

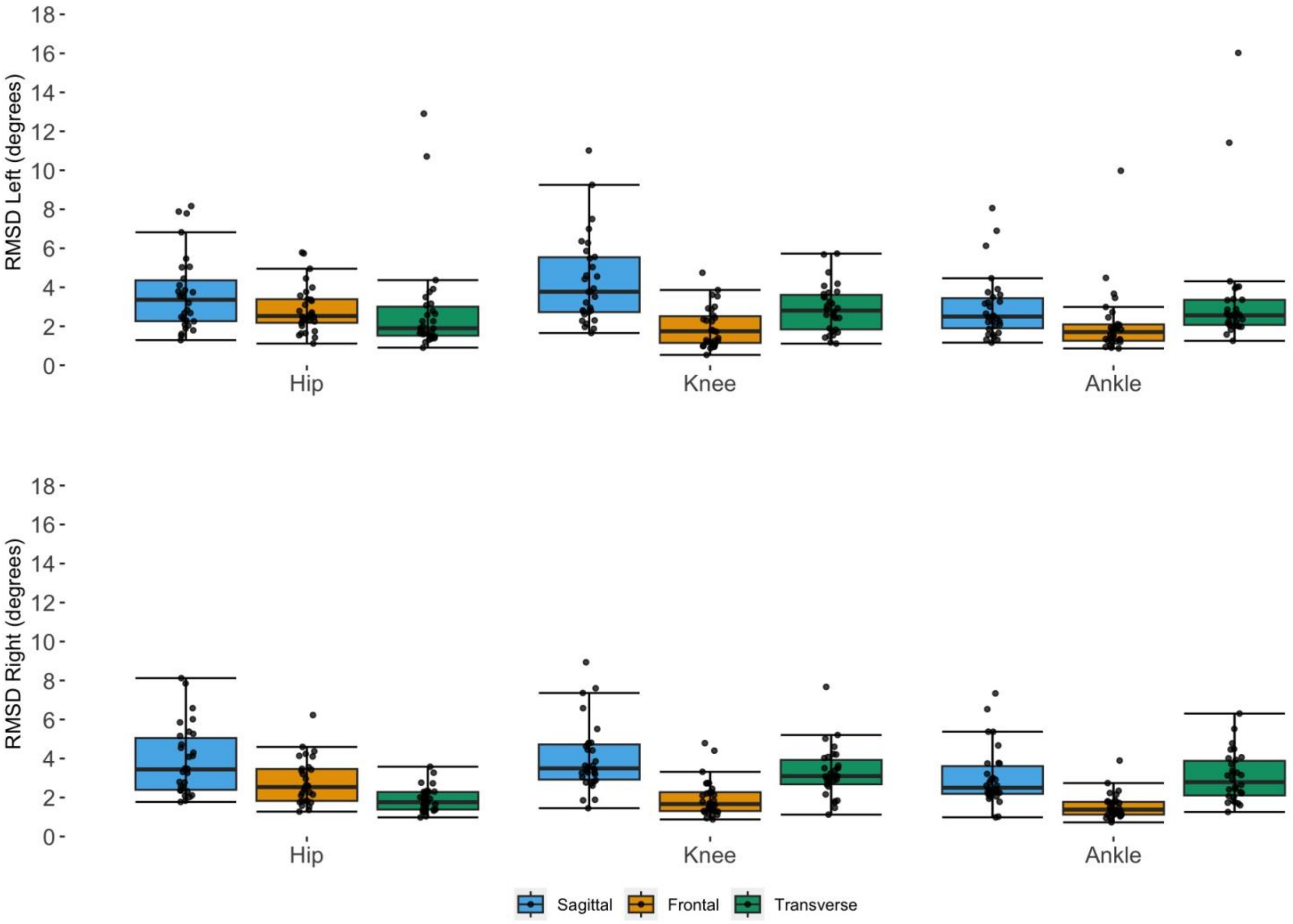


Figure 4.3. *Boxplots representing the root-mean-square deviation between the kinematic waveforms in the Conventional and Street conditions (n = 30). Each superimposed dot represents one participant.*

4.4.3 Participant and Caregiver Perceptions

Most participants felt positively towards both assessments (see Appendix G, Figure G.1). During the Conventional condition, one participant indicated feeling unhappiest, 3/26 felt neutral, and 81% felt happy (8/26) or happiest (13/26). During the Street condition, no participants indicated feeling unhappy and only 1/26 participants felt neutral, while 95%

indicated feeling happy (13/26) or happiest (12/26). Differences in participant perceptions were clearer when they were asked which condition(s) they would be willing to repeat. Fewer than one-third (7/25) were willing to repeat the Conventional condition, over 21/25 (80%) were willing to repeat the Street condition while one participant would not repeat either condition. A few participants provided further context for their preference. Those that preferred the Street condition stated it “felt more natural”, was “more casual”, and liked that they could “wear [their own] clothes”.

Most caregivers (12/18) felt the walking performed in either assessment was typical. Two caregivers felt the participant walked atypically in both assessments and four felt the participant walked atypically in the lab-based clothing assessment only (see Appendix G, Figure G.2).

4.4.4 Assessment Time

The median time to complete the Conventional condition was 14 minutes (11 mins, 17 mins), while the median Street condition lasted 3 minutes (2 mins, 3 mins). A Wilcoxon-Signed Rank test indicated the Street condition was significantly ($Z = -4.787$, $p<0.001$) faster than the Conventional condition with a median time difference of 11 minutes (9 mins,13 mins) (see Appendix G, Figure G.3).

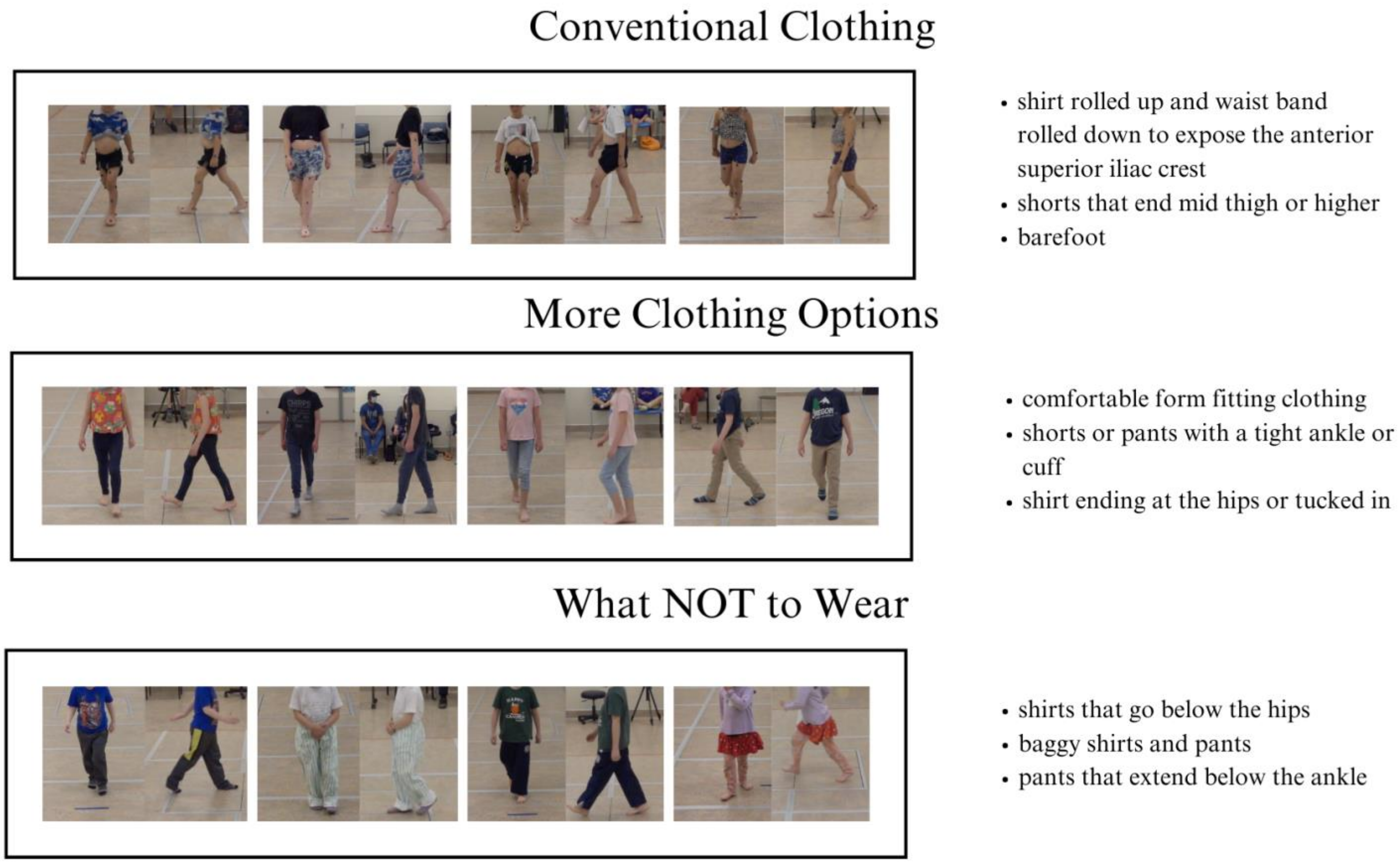
4.5 Discussion

This study demonstrated that some but not all styles of clothing can be worn during a 3D-GA without adversely impacting the gait kinematics. We also found evidence that markerless approaches results in a better participant experience when completing 3D-GA. We evaluated the impact of clothing condition on markerless kinematics, explored the participants’ perception of Conventional and less restrictive (Street condition) 3D-GA methods, and analyzed the time required to complete each condition.

4.5.1 Impact of Clothing on Joint Kinematics

Despite no constraints on the clothing worn during the Street condition, we found the overall agreement between the two conditions to be within clinically acceptable ranges. Joint angle RMSDs between the two clothing conditions had median RMSDs less than 4º, with all joints in the sagittal plane having RMSDs representing less than 10% of the mean range of motion in each joint which represents a good result when compared to the inter-session reliability establish in marker-based systems. Literature indicates error rates of 2 to 5º can be expected between sessions when marker-based systems are used, and a difference of less than 5º is clinically acceptable (13).

In determining what is appropriate to wear during a gait assessment, clinicians and analysts must be aware of how clothing can impact the kinematic waveforms. The overall difference between the two conditions was minimal; however, there were small changes in the shape of the waveforms that could impact how the data is interpreted. The clothing styles that were frequently worn by those participants whose kinematic data had a lack of agreement between the two conditions in one more joints or plane should be noted and likely avoided for clinical collections. Interestingly, some participants had very consistent results between the two conditions despite wearing styles of clothing that resulted in high RMSDs for other participants. As the consequence of collecting poor data is high, we generated recommendations of clothing styles to avoid as they were associated with poor consistency in at least one of our participants. When clinicians are preparing for an assessment Figure 4.4 can be used to inform a set of instructions for how the patient should dress during the assessment.



Conventional Clothing

- shirt rolled up and waist band rolled down to expose the anterior superior iliac crest
- shorts that end mid thigh or higher
- barefoot

More Clothing Options

- comfortable form fitting clothing
- shorts or pants with a tight ankle or cuff
- shirt ending at the hips or tucked in

What NOT to Wear

- shirts that go below the hips
- baggy shirts and pants
- pants that extend below the ankle

Figure 4.4 *Recommendations of appropriate clothing to wear for 3D-GA. Conventional clothing is the current standard for completing a marker-based assessment where the shirt must be rolled up and the waistband of the pants must be rolled down to expose the pelvis. The second box depicts the 'street' clothing that provided good data (no RMSD outliers) during the street assessment, and the third box depicts what not to wear during a 3D-GA as this clothing caused poor agreement between the lab and street conditions (RMSD outliers).*

The caregivers reported on whether they were walking typically during both assessments. Interestingly, of the six caregivers who indicated that their child did not walk in their usual way during the Conventional condition, four of the participants had outliers in at least one plane of one joint in the RMSD analysis. Alterations to how the participants walk should be considered when interpreting the results of a gait assessment as the child may not be walking in their typical way. Two participants who were observed to walk differently had good agreement in all joint kinematics and followed the expected kinematic curves; however, spatiotemporal parameters were not compared between conditions and may be impacted (33).

4.5.2 Participant and Parent Perceptions

Previous studies have demonstrated conventional marker-based gait assessments impact the way children walk (e.g. Hawthorne Effects) (33, 71). Most of our caregivers reported typical walking during both assessments. However, more of the caregivers reported walking differently during the conventional condition. This could indicate a reduction in the Hawthorne effect when wearing “street” clothing which is only possible with a markerless systems. Awareness of being measured might decrease when the participants can wear their normal clothing. Other factors are known to contribute to Hawthorne Effects too. Clinicians and analysts should be aware of the impact that observing the children while they walk can have, reducing the number of people in the room during the assessment, and removing external measurement devices (beyond removal of the markers) could increase the likelihood that participants walk as they usually typically do (33).

Our participants were largely comfortable with both conditions; however, they did prefer the Street conditions. Participants indicated that they preferred not having the markers placed, being able to wear pants, and appreciated the briefness of the assessment. Implementing markerless systems could enable participants to wear clothing they are more comfortable in, thereby decreasing their overall discomfort during 3D-GA. Interestingly, a few participants mentioned that they preferred the marker-based assessment because they felt it was more interesting, more scientific and had an expectation that a marker-based assessment would result in a more precise assessment. If markerless systems are implemented, clinicians may have to ensure patients trust the markerless assessment.

4.5.3 Time Data

Our results indicated that the Street clothing assessment took ~3.5 times less time than the Conventional condition assessment. Our assessments were faster than the average time required for a clinical 3D-GA with a marker-based system (20 minutes for set-up including marker placement alone which was longer than our total time (49)). This is also consistent with our clinical experience where several factors contribute to more challenging and time-consuming marker placements. Three-dimensional gait assessments in the MAC lab are booked for at least three hours, this enables both a comprehensive physical exam and the gait assessment to take place during one appointment with the gait assessment taking over 2/3rds of the allotted time. The Conventional condition is analogous to a standard marker-based assessment; — Conventional assessment was conducted as a markerless assessment; however, the marker-based protocol was followed for required clothing, the placement of reflective markers, and the collection of a static trial— therefore, we would expect the implementation of markerless systems to greatly decrease the overall time patients spend in the lab during clinical gait assessments.

Our sample size does not enable separate analysis based on potential age differences, future studies could investigate the efficiency of 3D-GA systems across the lifespan to determine the age group that would benefit the most from implementation of markerless systems in clinical settings.

4.5.4 Limitations

Several limitations to this study that warrant further discussion. The markerless system is not validated for use in pediatric populations and a direct comparison to the marker-based data was not completed in this study. Fourteen participants opted to wear the same shirt in both conditions and 12 opted to wear socks during both assessments, thus limiting our ability to interpret the impact of shirt choice or socks on the kinematic variables. Shoes were not worn for either condition and are not included in these recommendations. The age of the children is also a limitation, as a collection of survey data from pre-school age children is challenging as their attention spans are limited after completing a lengthy gait assessment and their understanding of the questions is limited. The modest sample size prevented exploration of the impact of age on our results.

4.6 Conclusion

Our results indicate that markerless motion capture for pediatric populations (both typically developing and clinical) makes the assessments more patient-friendly. Removing the need for markers and the related required clothing reduces patient discomfort and assessment time. The significant decrease in in-lab time for the participant and much faster processing times would save costs and could increase the number of patients seen in a lab each year.

4.7 Contribution of Authors

The authors confirm their contribution to the manuscript as follows: study conception and design: Amanda Rande, Ion Robu, Gina Ursulak, Gregor Kuntze, Elise Laende, Jereme Outerleys, Ranita H.K. Manocha, Rubini Pathy, Elizabeth G. Condliffe; data collection: Amanda Rande, Mahika Sharma, Ion Robu, Gina Ursulak; analysis and interpretation of results: Amanda Rande, Mahika Sharma, Ion Robu, Elizabeth G. Condliffe; draft manuscript preparation; Amanda Rande, Elizabeth G. Condliffe. All authors reviewed the results and approved the final version of the manuscript.

4.8 Acknowledgements

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Chapter 5: Conclusion

5.1 Summary of Findings

The purpose of this research was to validate markerless motion capture for pediatric populations including those with mobility impairments and determine the factors that impact the modality's usability for clinical gait analysis.

Previous literature investigating the concurrent validity of markerless motion capture has focused on adult populations. Our analysis of pediatric populations with and without mobility impairments shows slightly higher RMSDs than healthy adult population (33) but was similar to other literature investigating the validity of markerless systems for adolescents with cerebral palsy (55, 56).

Traditional marker-based assessments require participants to wear tight clothing or clothing that can be rolled and taped to expose the pelvis for marker placement. For individuals who are not comfortable wearing this clothing, the assessment can be intolerable. We compared the kinematic data from participants wearing the Conventional lab required clothing and the Street clothing they arrived at the lab in. We found that the majority of outfits that participants arrived at the lab wearing provided good kinematic data, but there were common patterns among the clothing that resulted in statistical outliers. Therefore, a brief guideline on what can be worn and what should be avoided for a markerless clinical gait assessment was created. The implementation of markerless systems would enable participants and patients to wear clothing they are more comfortable in as long as their clothing is relatively form-fitting (no large billowing tops or pants), their pants end above their ankles or are cuffed, and their shirt ends above their hips.

While the majority of participants were comfortable completing both the marker-based and markerless assessments some participants indicated they they preferred the markerless assessment. These participants stated that they preferred wearing clothing they were comfortable in, not having their pants and shirts taped to expose their pelvis and liked the briefness of the markerless assessment.

During gait assessments, we assume the participant is walking as they usually would. However, the act of being observed and measured actively changes the way people behave. The Hawthorne effect is an observable phenomenon where the behaviour of a participant will change while participating in research due to their knowledge that they are being observed. The Hawthorne effect has been shown to change how children walk in the laboratory setting and can have impacts on their spatiotemporal parameters (33, 67) We asked our participant's caregivers if they were walking like they typically do when they were wearing the markers and when they were completing the Street Condition. In general, our participant's caregivers reported walking typically during both assessments. However, more of the caregivers reported the participant was walking differently during the Conventional Condition (participants wearing markers) than they did in the Street Conditions (wearing their everyday clothes), this could indicate a reduction in the Hawthorne effect when the external measurement devices (markers) are removed. Two of the participants who were identified as walking in an untypical manner by their caregivers also had outliers in one plane or joint of their RMSD clothing comparison. We assume that the participants walked the same in both conditions and therefore the outlier is caused by their clothing, but the Hawthorne effect could be impacting the overall gait of participants when marker-based systems are used.

Clinical gait assessments are lengthy appointments that can be burdensome for some participants. Markerless assessments were a median of 11 minutes faster than their marker-based counterparts. We believe this difference underpredicts the time difference that would occur if markerless systems were implemented clinically as the placement of markers on patients who may have small anatomy, or surgical scars can be challenging and time-consuming. By removing the need to place markers patients could walk more casually and complete their assessments much faster. The decrease in time could not only decrease patient burden but may also decrease the clinician time required to complete an assessment – as often 2-3 staff are present for the assessment including marker placement; therefore, decreasing the healthcare cost associated with each assessment.

5.2 Limitations

Limitations of this study include the lack of a true gold standard for validation, the lack of generalizability of results to other markerless systems, difficulties with survey creation and execution, and the use of consumer-grade equipment.

5.2.1 Lack of a True Gold Standard

Throughout this study, marker-based motion capture is treated as the 'gold' standard. However, marker-based motion capture is not a true gold standard for clinical gait analysis has several limitations and issues that can decrease the reliability and validity of the data collected. Bone pin studies are the true gold standard for determining joint motion during gait as they are not impacted by skin movement artifacts (10). However, these studies are highly invasive and are not feasible for pediatric gait analysis. Moving fluoroscopy-based analysis is a close second for the gold standard as it can measure the in-joint motion without having pins inserted into the bones (56) but fluoroscopy requires highly specialized equipment a large lab space, and exposes participants to radiation; therefore, marker-based motion capture is the most frequently used method of conducting 3D-GA and is considered the clinical standard. Comparing markerless systems to marker-based standards is a limitation as the measures can be impacted by skin movement artifact and it relies on the accurate placement of markers on bony landmarks that are then visualized with infrared cameras. The transverse plane is notoriously difficult to measure and making conclusions about whether marker-based or markerless motion capture is more accurate in this plane cannot be completed unless both systems are compared to moving-fluoroscopy or bone pin data.

5.2.2 Issues of Generalizability

The lack of generalizability between markerless systems is a major limitation for applying the results of this study in gait labs. The results presented here are specific to Theia3D's approach and specific to version v2024.02.2 of Theia3D. Our results cannot be used to determine the validity of other markerless technologies or determine the impact of clothing conditions when other systems are used.

Generalizability of gait research can be challenging as many studies utilize small sample sizes causing the study to be underpowered for differentiating among population groups. Sex and age are two of the largest differentiators when analyzing gait data in typically developing populations. It is important to recruit a sample that includes an equal (or representative) number of males and females to ensure sex differences are not impacting the data when working with typically developing participants. When working with pediatric populations, it is important to consider differences throughout maturation not just between sexes (27). To ensure age is not a factor in the analysis studies could create age bands that reflect typical gait development and intentionally recruit participants within those bands (72). One study suggests that the number of strides analyzed could be just as important as overall sample size, as they found that in a sample of typically developing children, 28% of their strides did not fall within the normative band and therefore, were classified as abnormal (73). Stride-to-stride variability when working with pediatric populations can be high, this should be taken into account when designing a study and determining sample size.

Our studies recruited an equal number of males and females (in the typically developing cohort); however, data loss resulted in unequal sex proportions. This is not necessarily a limitation to our studies, as we did not directly compare sex; however, it should be considered when recruiting for future studies.

The sample size for our typically developing cohort was set to match the annual average number of three-dimensional assessments the MAC lab conducts. Sex and age were not variables of interest for these studies and were not considered as confounding factors in our analysis as we recruited a balanced sample; therefore, the sample size recruited was appropriate for addressing the overarching question of how accurate is markerless motion capture for pediatric populations without mobility impairments and is similar in size to other studies in this field. The results of our survey data are exploratory in nature and are likely underpowered, due to the small sample size (n=26) and heterogenous nature of the sample —large age range with several participants below school age (<6 years)— limited statistical analyses were conducted. The results cannot be generalized to a larger population but can be used as guidance for future research. However, the same limitations do not apply to the kinematic comparison between systems, as the heterogenous nature of our sample population increases the likelihood that our results are applicable to a larger population of children.

5.2.3 Survey Challenges

A limitation of understanding the factors that impact the usability of markerless motion capture is the difficulty of collecting written survey data from children who are younger than school-aged (<6 years) as they are typically unable to read the questions or write their responses without assistance. When assistance is provided to the participants there is always a risk of the parent or researcher unintentionally inserting their own bias into how the child answers or the risk that the child does not understand the question. The data presented within this study relating to the surveys was limited as the survey was not validated ahead of time and some of the questions in the full questionnaire invalidated themselves. An unexpected limitation to the caregiver survey data was the large sample of caregivers who worked within the Alberta Children’s Hospital and who were either tangentially involved in the research through other research activities within the lab, were present at presentations informing clinicians about the research, or had pre-conceived ideas of the study. The large sample size of clinicians as caregivers and the use of the HICCUP list whose members have often participated in previous research studies for recruitment increased the number of children participating who were familiar with research and were comfortable in a lab setting. This may have impacted their overall perceptions of the assessments, as I have the general sense that these participants were more interested in the research and the equipment than the children who were unrelated to clinicians or had never participated in research. Therefore, the sample was biased towards a positive experience, future research should recruit a random sample to reduce this bias.

5.2.4 Limitation of Consumer Grade System

The markerless system selected for this research is a commercial product; therefore, there are limited details relating to segmental and model definitions made available to the user. The location of the salient features the algorithm is trained on, the demographics of the training data set (age, sex, body habitus, presence of differing anatomy), and the location of the visual markers used to create the model have not been disclosed to the user. The lack of knowledge available to the user introduces a challenge when validating the system, as differences observed between the marker-based and markerless systems cannot be easily investigated or explained. A bulk of literature validating Theia3D in different populations and under different conditions concludes that segmental definitions are likely the cause of many of the offsets observed in the kinematic data, this creates a limitation in determining the true differences and the cause of those differences between the systems.

A limitation of this research and the clinical implication of this system is the use of consumer-grade Sony cameras. Clinical gait assessments at the Alberta Children's Hospital collect both kinematic and kinetic data. The Sony cameras record at 119.9 frames per second and are not capable of synchronizing with the force plates embedded in the walkway used for data collection. This drastically decreases the overall usability of the system as kinetic data cannot be appropriately or accurately synchronized with force data, therefore eliminating the use of joint forces and joint moments that provide important information for clinical decision-making. The control of the cameras through Sony's web interface creates additional challenges as the interface is slow to respond, and the cameras frequently lose contact with it. The consumer-grade web interface does not allow the researchers to control the cameras with precision and frequently causes data loss and increases researcher time required before and after data collection sessions. If short trials (<5 seconds) are recorded, the cameras will overwrite the memory card, causing the current trial or previous trial to be lost or the camera that is attempting to write to the memory card will lose contact with the web interface and turn off, thus causing an entire recording or multiple recordings from that trial to be lost. The Sony system is unreliable and has a high risk of data loss; therefore, it is not an appropriate system for clinical assessments where children may walk at variable speeds (too quickly for the cameras to write to the memory cards), assessments may occur sporadically (cameras need time to warm-up), or when data from other systems need to be synchronized with the kinematic data (i.e. force data or electromyography).

5.3 Clinical Implications

When referring patients for a clinical gait assessment, clinicians could recommend the use of markerless motion capture for patients whose sagittal plane data is the most pertinent, who are uncomfortable wearing tight clothing, who have sensory sensitives and who may not tolerate marker placement, or for those who fatigue quickly and would benefit from a faster assessment. When concurrently compared to the clinical standard marker-based system, markerless motion capture produced similar waveforms with median RMSDs and MAE less than 6º in all joints aside from the transverse plane of the hip and knee. The preliminary validation of Theia3D for pediatric populations with and without mobility impairments situates markerless motion capture as a viable option for conducting assessments in patients whose clinical question does not require the analysis of motion in the transverse plane.

Markerless motion capture provides a more patient-friendly experience as patients can wear clothing, they are more comfortable in as long as it is not overly baggy, their shirt ends at or above their hips, and their pants are cuffed or end above the ankle. Markerless assessments were a median 11 minutes faster than the marker-based assessments, which likely underestimates the time difference that would be observed in a clinical population. The speed of the assessments, the removal of the markers, and the ability to wear clothing they are more comfortable wearing, significantly decrease the patient burden of completing a clinical gait assessment if the system is implemented in clinical gait labs.

5.4 Future Directions

Investigations into the accuracy of markerless systems have mainly focussed on healthy adults, future research should address pediatric populations with and without different mobility impairments while using different styles of walking aids, while wearing orthoses, and while wearing more constrained clothing conditions. Studies investigating the validity of markerless motion capture are limited to concurrent validity (without a true gold standard for comparison) and do not address the other areas of validity or follow a validation framework to fully explain the bounds of its use. Future studies should include other areas of validity to expand the level of evidence relating to markerless technologies. Furthermore, there is limited research investigating the factors that impact the usability of marker-based or markerless motion capture for pediatric clinical gait assessments. Future research should examine the perceptions of patients after they complete a clinical gait assessment to better inform clinical practice and to reduce the patient burden of these important assessments. Further examining how the caregivers of patients perceive the assessments and their perceptions of how their child walks while at home or in a community setting compared to how they walk in the lab with and without markers placed may also provide information into how the Hawthorne effect may impact the data collected during assessments and provide insights into how to mitigate its impact.

5.5 Conclusion

This research provides further evidence for the validation of markerless motion capture for conducting clinical gait assessments with pediatric populations with and without mobility impairments. Markerless motion capture had good agreement in all joints, except in the transverse plane of the hip and knee when compared with the current marker-based standard. Participants were more comfortable completing gait assessments without the use of reflective markers and while wearing their own clothing and appreciated the quickness of markerless assessments as opposed to marker-based. The findings of this study suggest that markerless motion capture may decrease the overall patient burden of clinical gait assessments by decreasing assessment time and increasing patient comfort by allowing patients to wear clothing they are comfortable in. These findings can be used to inform the implementation of markerless motion capture in pediatric gait labs.

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Appendix A. Recruitment Materials

PARTICIPATE IN RESEARCH!

Markerless Motion Capture

- Complete a walking trial using 2 motion capture systems
- Data collection takes around 1hr
- Looking for multicultural participants
- Ages 4 to 18 years old
- Contact Amanda at poni.lab@ucalgary.ca

PARTICIPATE

ARTIFICIAL INTELLIGENCE FOR INSTRUMENTED GAIT ANALYSIS

Come participate in our research assessing markerless motion capture technology.

Participant requirements:

- between 4 and 18yrs old
- no recent injuries
- tpyically developing with no neurological impairments or recent concussions

Multi-Cultural Participants Wanted!

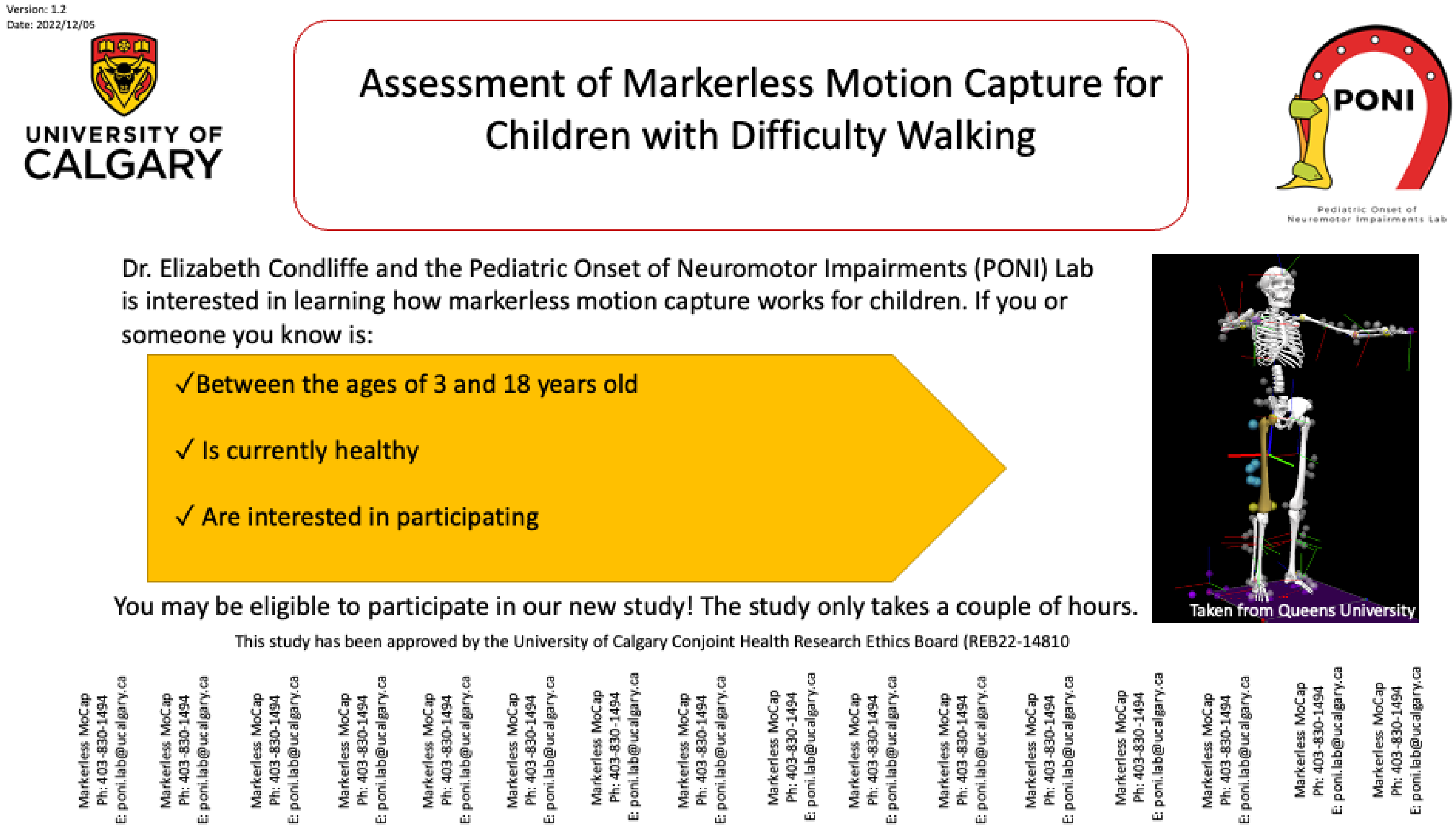
Markerless motion capture for analyzing pediatric gait

Location: Alberta Children's Hospital Movement Assessment Centre

Time: One session around 1 hour

Tasks: Walk back and forth along a platform with markers on your skin Change into your street clothes and keep walking!

Figure A.1 *Recruitment flyers formatted as instagram posts. Pictures used to recruit participants through social media.*



Version: 1.2
Date: 2022/12/05

UNIVERSITY OF CALGARY

Assessment of Markerless Motion Capture for Children with Difficulty Walking

PONI
Pediatric Onset of Neuromotor Impairments Lab

Dr. Elizabeth Condliffe and the Pediatric Onset of Neuromotor Impairments (PONI) Lab is interested in learning how markerless motion capture works for children. If you or someone you know is:

- ✓Between the ages of 3 and 18 years old
- ✓ Is currently healthy
- ✓ Are interested in participating

Taken from Queens University

You may be eligible to participate in our new study! The study only takes a couple of hours.

This study has been approved by the University of Calgary Conjoint Health Research Ethics Board (REB22-14810

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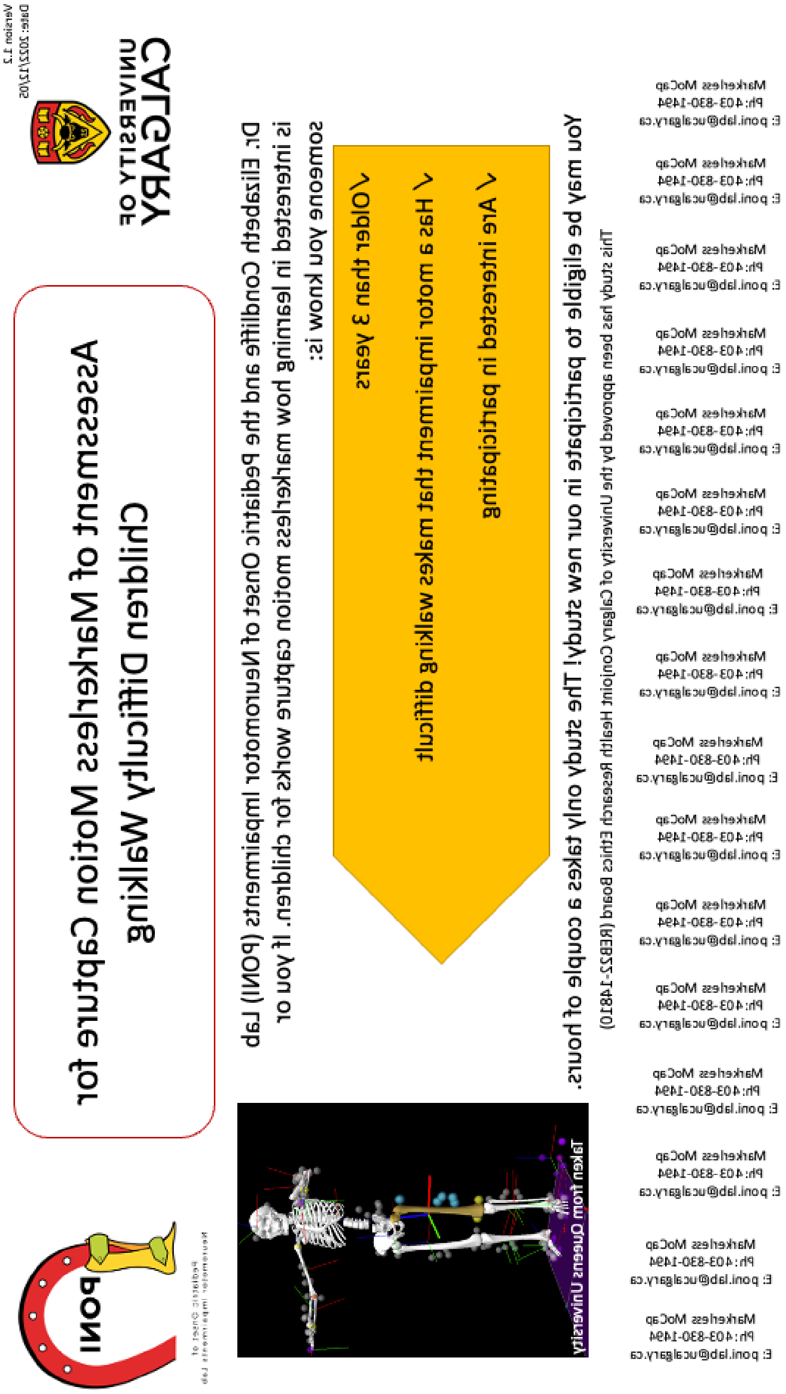
Figure A.2 *Recruitment Poster for the Typically Developing Cohort. Posters were placed around the Alberta Children's Hospital.*



Version 1.2
Date: 2022/12/05

Assessment of Markerless Motion Capture for Children Difficulty Walking

Dr. Elizabeth Condliffe and the Pediatric Onset of Neuromotor Impairments (PONI) Lab is interested in learning how markerless motion capture works for children. If you or someone you know is:

- √Older than 3 years
- √ Has a motor impairment that makes walking difficult
- √ Are interested in participating

Taken from Queens University

You may be eligible to participate in our new study! The study only takes a couple of hours.

This study has been approved by the University of Calgary Conjoint Health Research Ethics Board (REB22-14810)

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Figure A.3 *Recruitment Poster for Children with Mobility Impairments. Posters were hung in the Alberta Children's Hospital's Neuromotor wing to recruit participants when they attended clinic.*

Appendix B. System Orientation

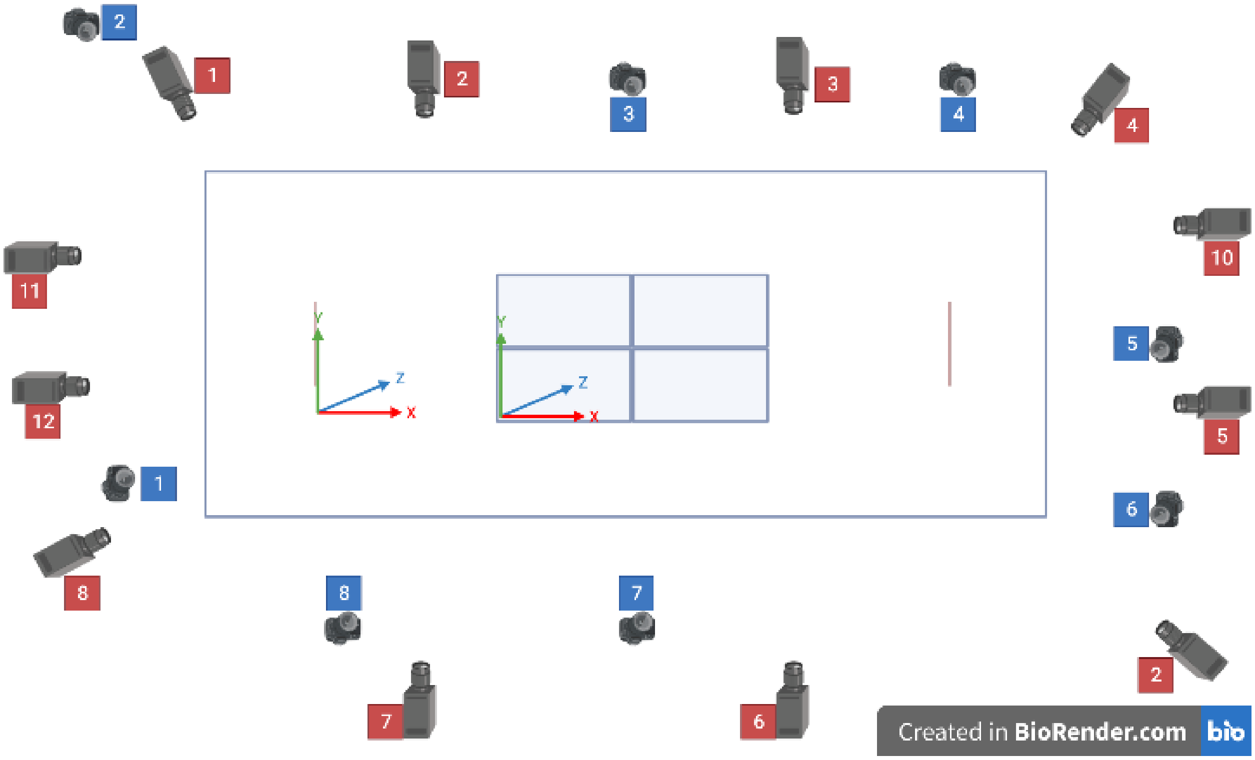


Figure B.1 *Orientation of the Movement Assessment Centre (MAC) and required motion capture equipment. Blue cameras identify the approximate locations of the video cameras used for the markerless analysis. Cameras labelled in red illustrate the approximate location of the infrared cameras used for marker-based motion capture. The red lines indicate the end of the calibrated range for the marker-based system. The four rectangles in the centre of the figure are faceplates embedded into the walkway. The origin of the marker-based motion capture system is located in the corner of the force plates while the origin for the markerless system aligns with the border of the calibrated volume.*

Appendix C. Data Collection and Extraction Methods for Typically Developing Participants

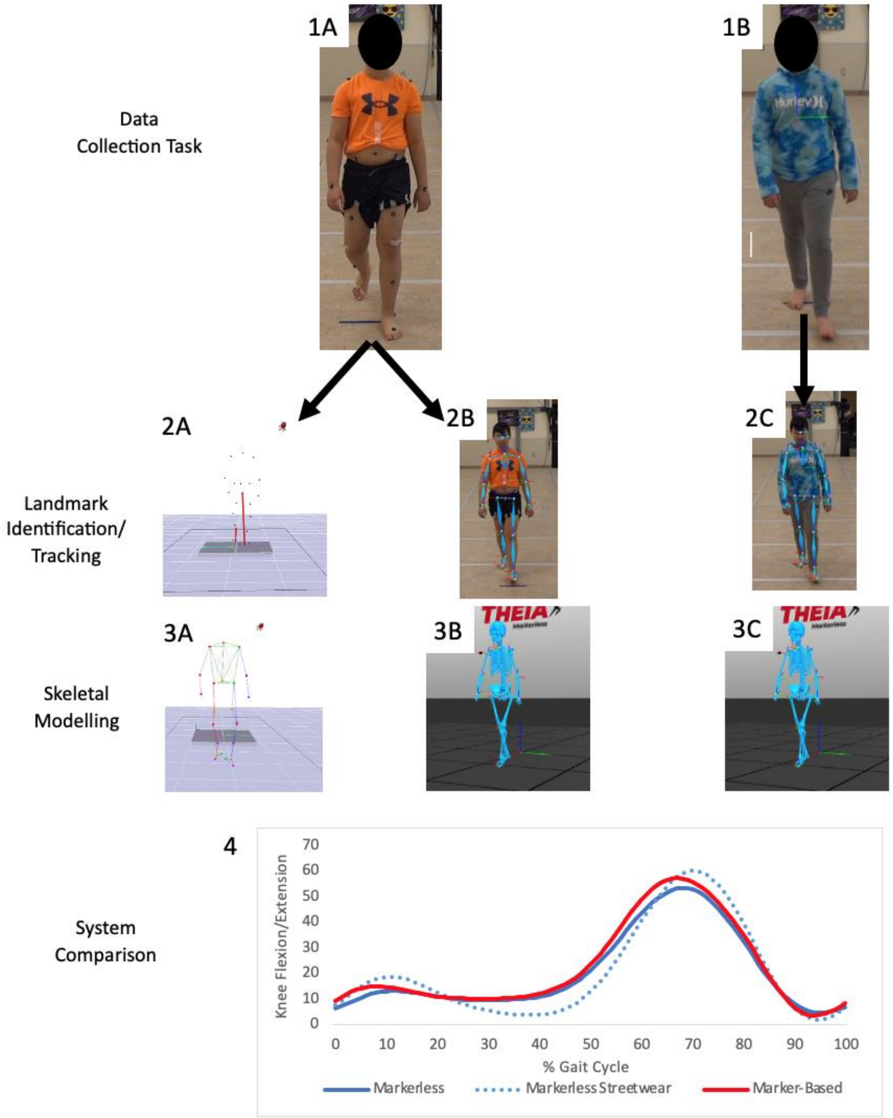
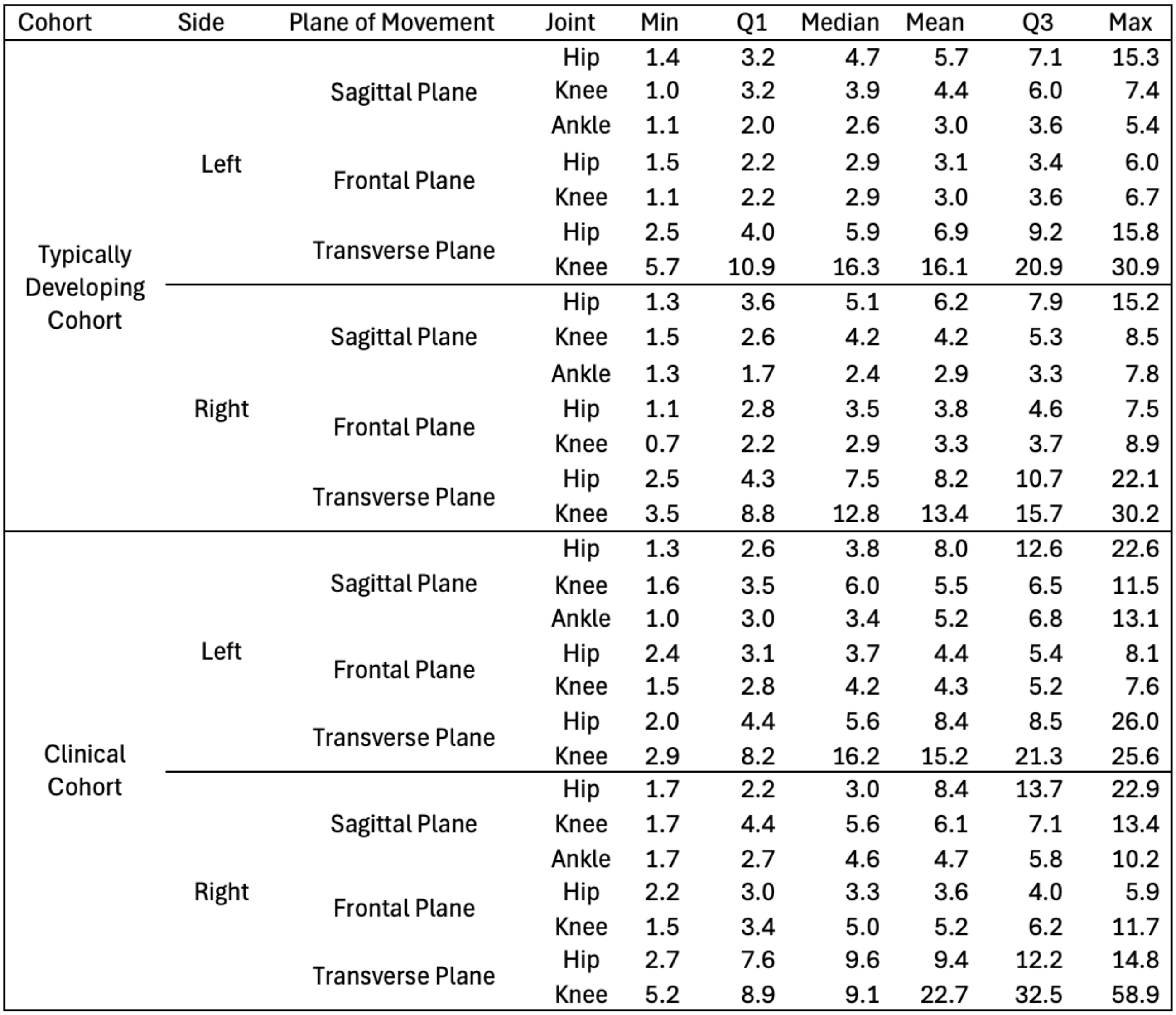


Figure C.1 *Example of Data Collection and Extraction Workflow for the Typically Developing Participants. Participants completed a typical marker-based gait assessment (image 1A) and a markerless-only assessment (image 1B – referred to as the Street Condition in the text). Initial date extraction (2A, 2C) was completed in the respective motion capture software while further kinematics were calculated using Visual3D for both systems before being compared (image 4).*

Appendix D. Descriptive Statistics Assessing the Concurrent Validity of Markerless Motion Capture

Table D.1 *Descriptive statistics comparing the root-mean-square-deviations (RMSD) calculated between the marker-based and markerless systems (n=28).*



Cohort	Side	Plane of Movement	Joint	Min	Q1	Median	Mean	Q3	Max
Typically Developing Cohort	Left	Sagittal Plane	Hip	1.4	3.2	4.7	5.7	7.1	15.3
			Knee	1.0	3.2	3.9	4.4	6.0	7.4
			Ankle	1.1	2.0	2.6	3.0	3.6	5.4
		Frontal Plane	Hip	1.5	2.2	2.9	3.1	3.4	6.0
			Knee	1.1	2.2	2.9	3.0	3.6	6.7
		Transverse Plane	Hip	2.5	4.0	5.9	6.9	9.2	15.8
			Knee	5.7	10.9	16.3	16.1	20.9	30.9
	Right	Sagittal Plane	Hip	1.3	3.6	5.1	6.2	7.9	15.2
			Knee	1.5	2.6	4.2	4.2	5.3	8.5
			Ankle	1.3	1.7	2.4	2.9	3.3	7.8
		Frontal Plane	Hip	1.1	2.8	3.5	3.8	4.6	7.5
			Knee	0.7	2.2	2.9	3.3	3.7	8.9
		Transverse Plane	Hip	2.5	4.3	7.5	8.2	10.7	22.1
			Knee	3.5	8.8	12.8	13.4	15.7	30.2
Clinical Cohort	Left	Sagittal Plane	Hip	1.3	2.6	3.8	8.0	12.6	22.6
			Knee	1.6	3.5	6.0	5.5	6.5	11.5
			Ankle	1.0	3.0	3.4	5.2	6.8	13.1
		Frontal Plane	Hip	2.4	3.1	3.7	4.4	5.4	8.1
			Knee	1.5	2.8	4.2	4.3	5.2	7.6
		Transverse Plane	Hip	2.0	4.4	5.6	8.4	8.5	26.0
			Knee	2.9	8.2	16.2	15.2	21.3	25.6
	Right	Sagittal Plane	Hip	1.7	2.2	3.0	8.4	13.7	22.9
			Knee	1.7	4.4	5.6	6.1	7.1	13.4
			Ankle	1.7	2.7	4.6	4.7	5.8	10.2
		Frontal Plane	Hip	2.2	3.0	3.3	3.6	4.0	5.9
			Knee	1.5	3.4	5.0	5.2	6.2	11.7
		Transverse Plane	Hip	2.7	7.6	9.6	9.4	12.2	14.8
			Knee	5.2	8.9	9.1	22.7	32.5	58.9

Abbreviations - Q1: First quartile/ 25th percentile; Q3: Third Quartile/ 75th percentile; Min: Minimum; Max: Maximum

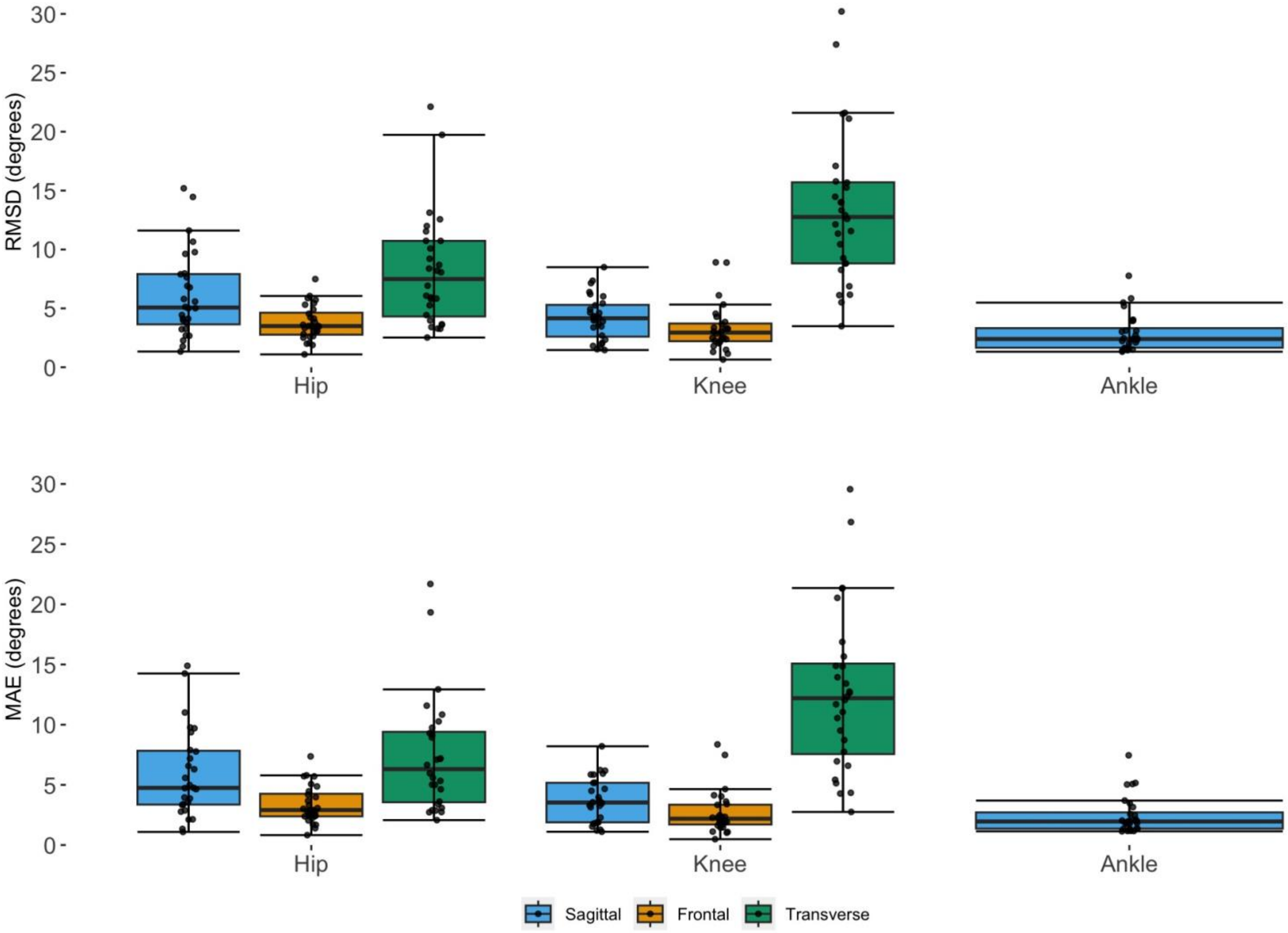


Figure D.1 *Boxplots illustrating the root-mean-square deviations (top) and mean absolute errors (bottom) observed between the marker-based and markerless systems for the right leg of the typically developing cohort (n=28).*

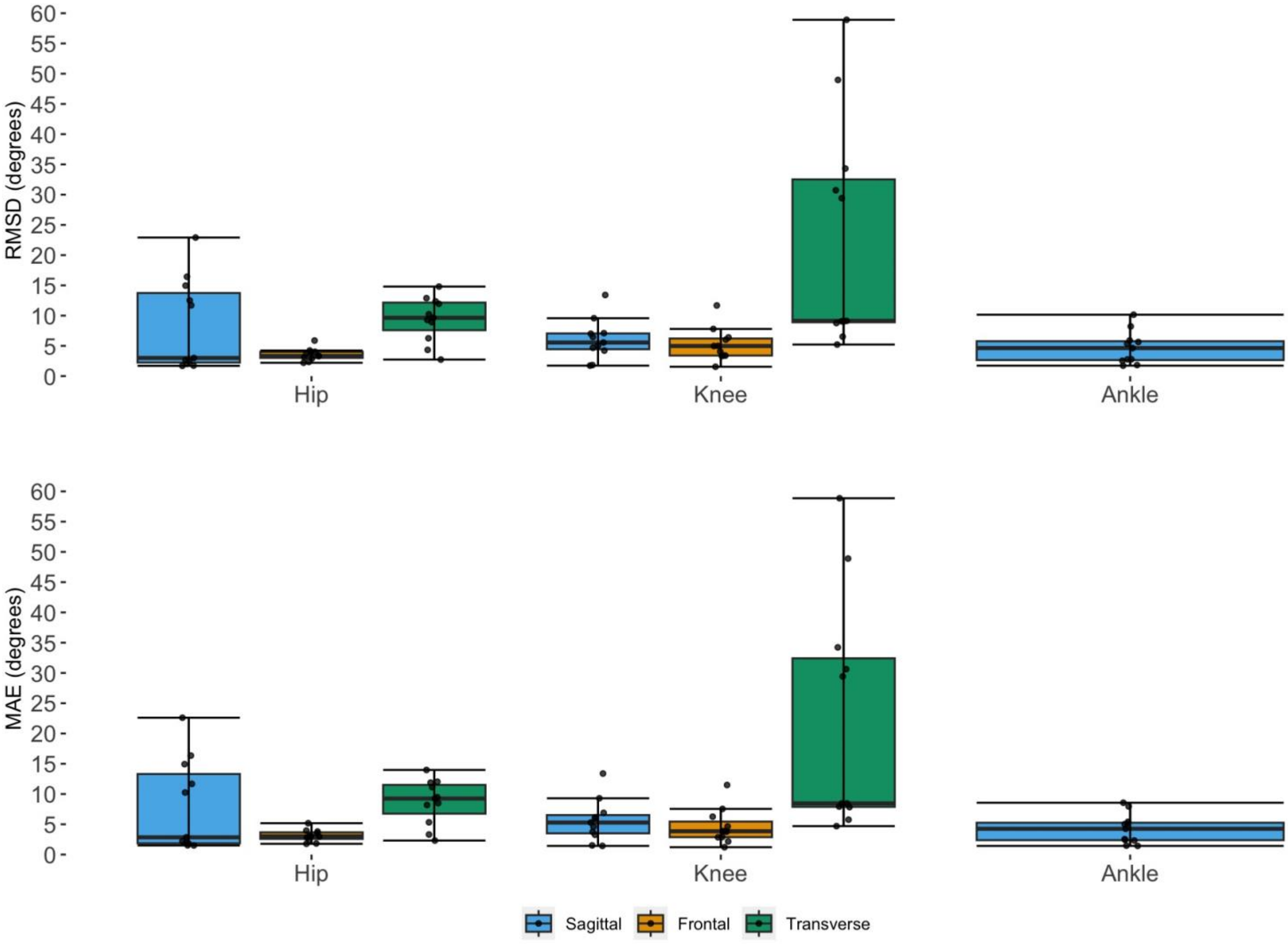


Figure D.2 *Boxplots illustrating the root-mean-square deviations (top) and mean absolute errors (bottom) observed between the marker-based and markerless systems for right leg of the clinical cohort (n=11).*

Appendix E. Assessing Concurrent Validity Between Marker-based and Markerless Motion Capture Systems

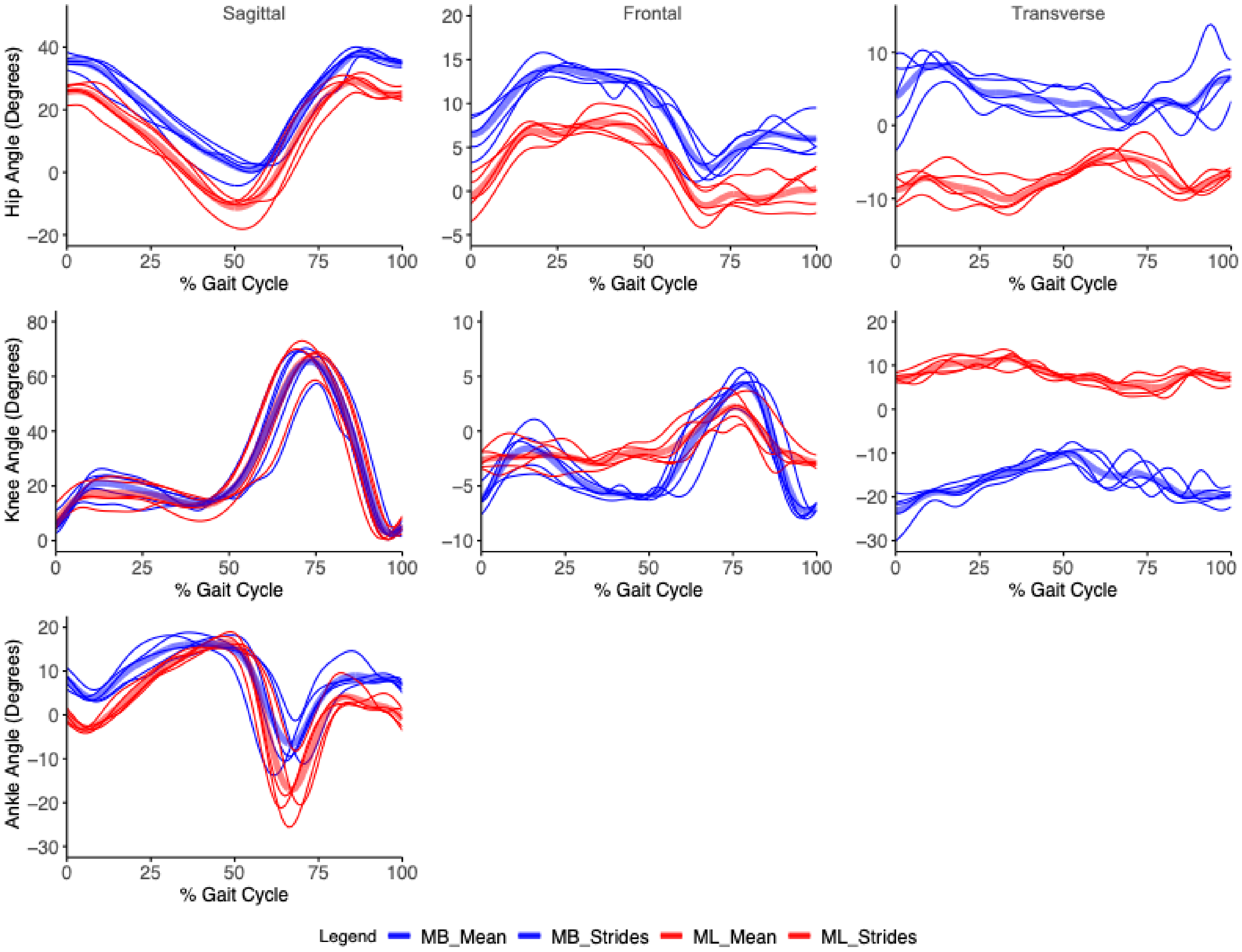


Figure E.1 *Representative kinematic waveforms between systems (marker-based and markerless) for the right hip, knee, and ankle of a five-year-old typically developing female (n=1). Thin blue lines represent strides collected using the marker-based system while the thicker and more transparent blue band represents the mean of the marker-based strides. Red lines represent strides collected using the markerless system while the more transparent red band represents the mean of the markerless strides.*

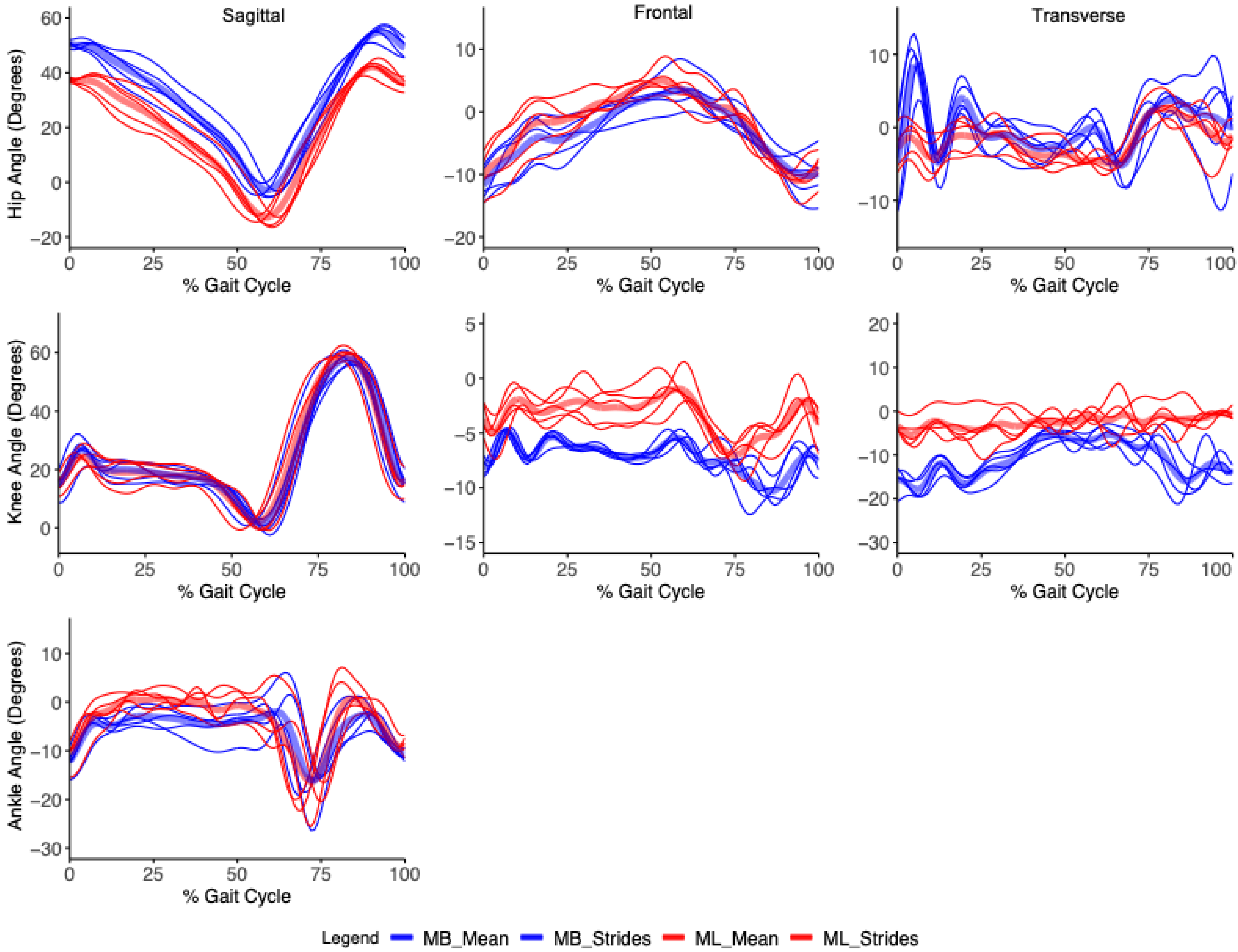


Figure E.2 *Representative kinematic waveforms between systems (marker-based and markerless) for the left hip, knee, and ankle of a ten-year-old male with cerebral palsy (n=1). Thin blue lines represent strides collected using the marker-based system while the thicker and more transparent blue band represents the mean of the marker-based strides. Red lines represent strides collected using the markerless system while the more transparent red band represents the mean of the markerless strides.*

Appendix F. Examining Differences Between Conventional and Street Clothing on 3D-GA

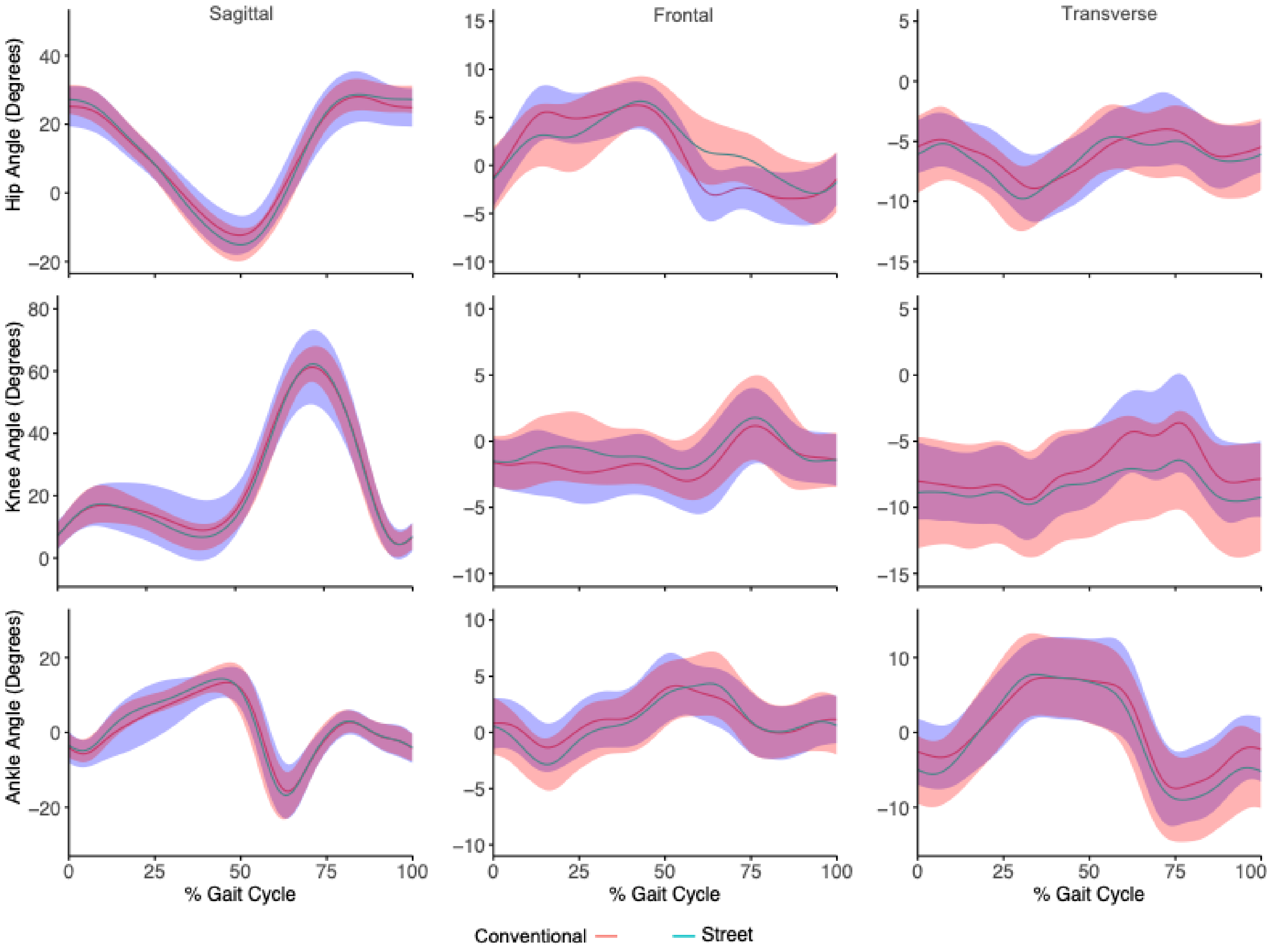


Figure F.1 *Kinematic waveforms comparing Conventional and Street clothing on the right leg of typically developing children (n=30). Conventional clothing is shown in blue with Street clothing in red. Bands of colour represent +/- 1SD around the mean. Purple bands represent the area where the standard deviation of both conditions overlap.*

Appendix G. Assessing Participant and Caregiver’s Perceptions of 3D-GA Under Two Clothing Conditions

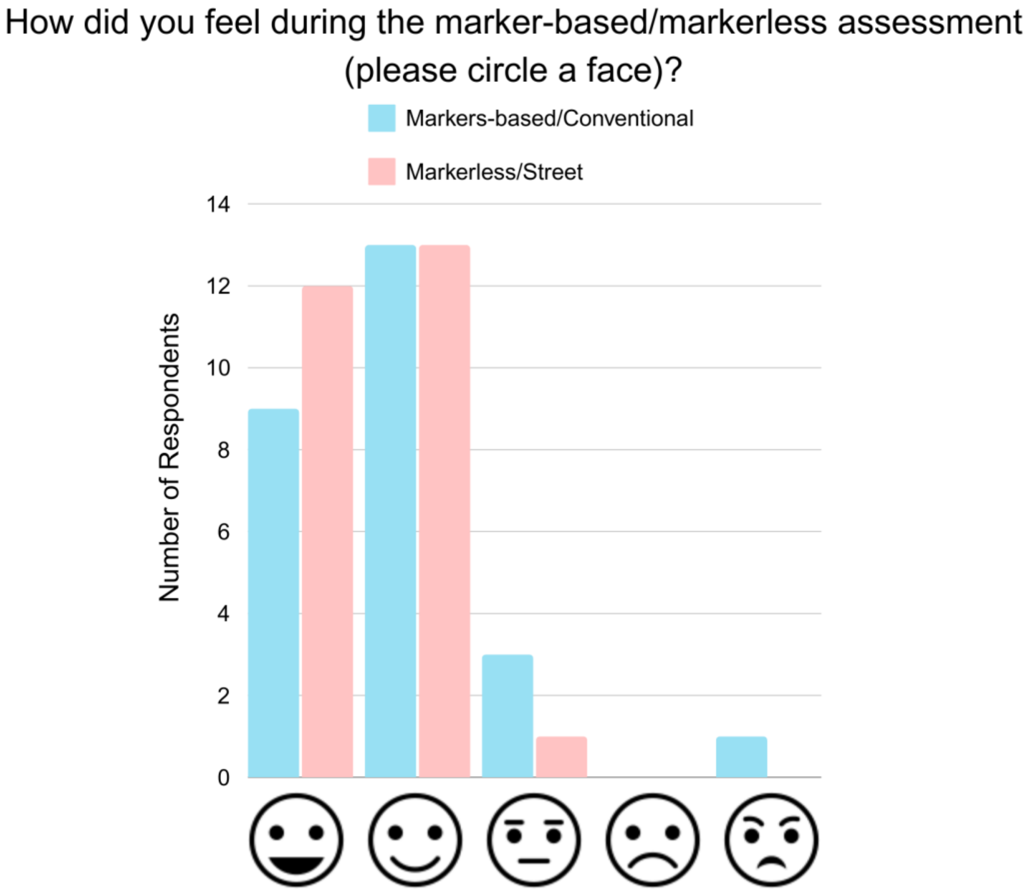


Figure G.*1 Bar graph representing participants’ (n=26) responses to the questions “How did you feel during the marker-based assessment”, and “How did you feel during the markerless assessment” where participants responded by circling a smiley face that best represented how they felt during each assessment. The pink bar represents responses to the markerless assessment (Street condition) while blue represents responses to the marker-based assessment (Conventional condition).*

		Markerless/Street		
		No	Yes	Total
Marker-based/Conventional	No	2	4	6
	Yes	0	12	12
	Total	2	15	18

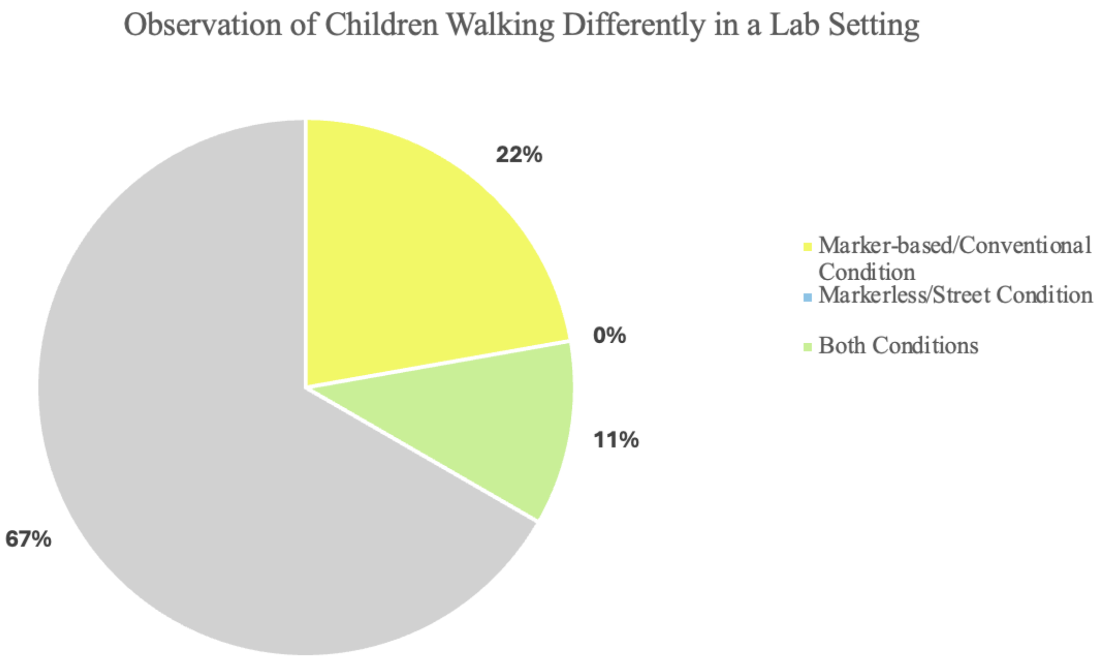


Figure G.2 *Caregiver (n=18) perceptions of how their child walks during the Conventional and Street assessment. A) 2x2 contingency table of caregiver's responses to the questions "Did your child walk as they usually do during X assessment?". B) Pie chart representing caregiver's responses to how their child walked in the lab setting. 67% of caregivers felt their child walked as they normally do (grey), 11% indicated their child walked differently in both conditions (green), and 22% felt their child walked differently in the marker-based (Conventional condition) assessment (yellow).*

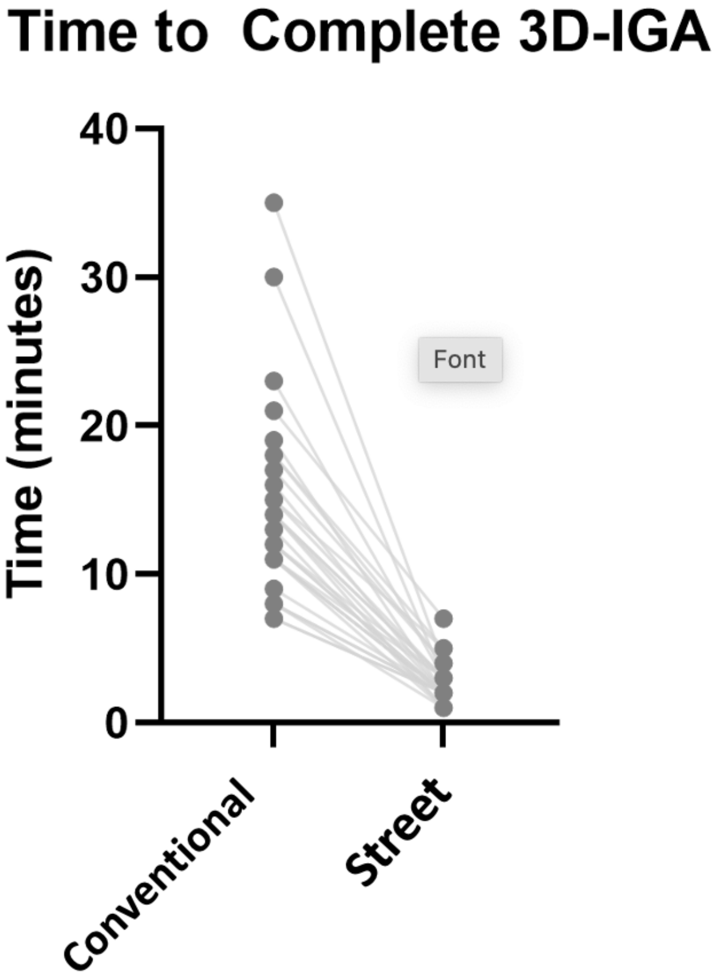


Figure G.3 *Dot plot comparing the time it takes to complete the Conventional condition (represents a typical marker-based motion capture session) compared to the Street condition (represents a markerless motion capture assessment where participants are wearing unrestricted street clothing). Each participant (n=30) is represented by a dot with lines connecting the same participant between conditions.*

Appendix H. Perceptions of Instrumented Gait Analysis Survey

H.1 Questions for Parent

Perceptions of artificial intelligence

1. Have you ever heard or read about artificial intelligence?
    a. Yes, I would consider myself an expert in that field
    b. Yes, and I could explain well what it is about
    c. Yes, and I know somewhat what it is
    d. Yes, but I don't know exactly what it is
    e. No, I have not heard of artificial intelligence
2. I trust the assessment completed by artificial intelligence
    a. Strongly agree
    b. Agree
    c. Neither agree or disagree
    d. Disagree
    e. Strongly Disagree
3. I trust artificial intelligence to accurately identify the joint landmarks
    a. Strongly agree
    b. Agree
    c. Neither agree or disagree
    d. Disagree
    e. Strongly disagree
4. Did you have any opinions on the use of artificial intelligence before participating in this study (if so, please explain)?
    a. Yes____
    b. No
5. Do you have any concerns about artificial intelligence (If so, please explain)?
    a. Yes____
    b. No
6. Do you have any concerns about collecting/using video data to perform gait analysis? (If so, please explain)
    a. Yes ____
    b. No
7. If your child were to repeat the assessment, would you prefer them to complete the markerless assessment or marker-based assessment? (Please explain)
    -
    ____
    ____
    ____

Participant ID	
Group	

Perceptions of the marker-based assessment

1. Do you think your child walked in their usual way when the markers were on their skin (if not, please explain)?
    a. Yes
    b. No____
2. I felt comfortable with my child completing the marker-based assessment
    a. Strongly agree
    b. Agree
    c. Neither agree or disagree
    d. Disagree
    e. Strongly disagree
3. The marker-based assessment took too long
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree

Perceptions of the markerless assessment

1. Do you think your child walked in their usual way during the markerless assessment (if not, please explain)?
    a. Yes
    b. No____
2. I felt comfortable with my child completing the markerless assessment
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
3. The markerless assessment took too long
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree

Participant ID	
Group	

H.2 Questions for participant

Perceptions of the marker-based assessment

1. I was comfortable with where the markers were placed
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
2. I was uncomfortable during marker placement
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
3. I was comfortable wearing the clothes I needed to for the assessment.
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
4. How did you feel during the marker-based assessment (please circle)

5. I walked like I usually do with the markers on my skin
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
6. I felt the markers were bugging (rubbing on you, itchy) me when I was walking
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
    f. What/where were the markers bugging you?
    ____
7. I was more comfortable completing the marker-based assessment
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree

Participant ID	
Group	

   d. Disagree
   e. Strongly disagree

8. At any point during the marker-based assessment did you feel uncomfortable (if yes please explain)?
   a. Yes____
   b. No

Perceptions of the markerless assessment

1. How did you feel during the markerless assessment (please circle)

2. I walked like I usually do during the assessment
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
3. I was more comfortable completing the markerless assessment
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
4. I preferred completing the assessment while wearing my everyday clothes
    a. Strongly agree
    b. Agree
    c. Neither agree nor disagree
    d. Disagree
    e. Strongly disagree
5. At any point during the markerless assessment did you feel uncomfortable (if yes please explain)?
    a. Yes____
    b. No
6. How did you find the length of the assessment?
    a. Very long
    b. Slightly long
    c. Not too long or too short
    d. Slightly too short
    e. Very short

Summary Questions

1. If you were to complete the assessment again, would you want to do the marker-based or the markerless, why?

2. Which assessment was your favourite, markerless or with the markers?