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The Use of Real-Time Feedback to Improve Kinematic Marker Placement Consistency Among Novice Examiners

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The Use of Real-Time Feedback to Improve Kinematic Marker Placement Consistency Among
Novice Examiners

by

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A THESIS

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Abstract

Marker placement deviation contributes the largest amount of error in gait kinematic data. The study purpose was to determine whether a novel, real-time marker-placement tool could improve consistency of gait kinematic data. Twelve novice examiners placed retroreflective markers on a single runner. For each examiner, a running trial was analyzed using two static trials: (1) PRE and (2) POST implementation of the feedback tool. The protocol was repeated a second time, one week later, resulting in PRE1, POST1, PRE2, and POST2 conditions. The 95% confidence interval (CI) of the mean joint angles for the entire stride, was compared between the PRE1/POST1, and PRE2/POST2 conditions. POST1 feedback trials showed a reduced 95%CI range for eight of nine joint angles compared to PRE1. POST2 trials reduced the 95%CI for five of nine joint angles compared to PRE2. The results indicate a real-time feedback tool improves kinematic marker placement consistency for novice examiners.

Preface

The methodology and results presented in Chapters 3-4 are based on the following manuscript submitted for publication:

Macaulay, C.A.J., Osis, S.T., Clermont, C., and Ferber, R. (2017). The use of real-time feedback to improve kinematic marker placement consistency among novice examiners. *Gait and Posture* (in review).

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List of Abbreviations

Abbreviation	Definition
2D	Two-dimensional
3D	Three-dimensional
3DGA	Three-dimensional gait analysis
ANOVA	Analysis of variance
AP	Antero-posterior
ASIS	Anterior superior iliac spine
CI	Confidence interval
CMC	Coefficient of multiple correlations
CMD	Coefficient of multiple determination
CP	Cerebral palsy
CV	Coefficient of variation
DLT	Direct linear transformation
GRF	Ground reaction force
ICC	Intraclass correlation coefficient
IQR	Inter-quartile range
IQRR	Inter-quartile range ratio
JCS	Joint coordinate system
OA	Osteoarthritis
OLGA	Optimized lower limb gait analysis
POST1	Corresponding to post-feedback static trial, day 1
POST2	Corresponding to post-feedback static trial, day 2
PRE1	Corresponding to pre-feedback static trial, day 1
PRE2	Corresponding to pre-feedback static trial, day 2
RMSE	Root mean square error
ROM	Range of motion
SCS	Segment Coordinate System
SD	Standard deviation
SE	Standard error
SEM	Standard error of measurement
VCM	Vicon clinical manager

CHAPTER ONE: INTRODUCTION

1.1 Introduction

Three-dimensional gait analysis (3DGA) is commonly used to analyze pathological gait and athletic performance in both clinical and research settings. Data collection protocols involve the careful placement of retroreflective markers on specific anatomical landmarks. The position of each marker is tracked using multiple, high speed, video cameras positioned specifically around the clinic or laboratory and aimed at the subject. Despite being considered the gold standard for gait kinematic data collection, 3DGA is subject to various sources of error that limit the validity of the data. Prior research has shown marker placement inconsistency to be the largest contributor of error in gait kinematics, resulting in up to 75% of the overall error seen in between-tester data collections (Gorton, Hebert, & Gannotti, 2009). Marker placement inconsistency can have severe implications on repeated measurement protocols that involve baseline and follow-up data collections, especially with protocols that involve multiple examiners. If the subject undergoes an intervention between data collections, such as a daily exercise routine, the changes in kinematics that are attributed to the intervention may be due instead to the marker placement inconsistency. In a laboratory setting researchers may be led to make unsound conclusions, while clinicians may be unable to make consistent diagnoses between patients, which can potentially misguide treatment in a clinical setting. Furthermore, the prospect of multi-centre collaboration and data sharing would provide researchers with access to larger and more diverse samples, while improving the generalizability of their results and allowing for consultation between experts from different clinics (Tirosh, Baker, & McGinley, 2010). However, without a protocol or device in place to mitigate the effect of this

inconsistency on the resulting gait kinematic measurements, the reliability of multi-centre collaboration efforts remain limited. 00

Over the past 35 years, research surrounding human gait kinematics has determined that various levels of consistency exist depending on the nature of the comparison being made (Gorton et al., 2009; Kadaba et al., 1989; Pohl, Lloyd, & Ferber, 2010; Winter, 1984). In particular, the consistency of an individual's gait kinematics can be determined by comparing data collected within- or between-days, and/or data collected by one examiner (within-examiner) or multiple examiners (between-examiner).

An early example in the literature is the work done by Winter (1984), exploring a single individual's walking kinematics and kinetics over multiple trials and days to determine within-subject consistency. The results showed that within-subject consistency is higher when considering kinematic joint angle data as opposed to the kinetic measurements of joint moment at the ankle, knee, and hip joints (Winter, 1984). However, Winter (1984) noted that ground reaction force (GRF) data, despite being a kinetic measure, showed the greatest consistency for within-subject measurements, as compared to joint moment or kinematic data. Considering GRF represents a sum of acceleration data of all individual segments of the body, the value remained consistent from one trial to the next despite differences in the individual kinetic measurements at each segment (Winter, 1984). Subsequent walking gait research supports the finding that GRF and kinematic measures display greater consistency within-subject than kinetic variables such as joint moments (Kadaba et al., 1989). Using the intraclass correlation coefficient (ICC), the same relationship has been observed for running gait as well (Ferber, McClay Davis, Williams, & Laughton, 2002). However, kinematic and kinetic measures showed similar levels of consistency ($ICC > 0.84$) while the GRF consistency was greater ($ICC > 0.90$) both within- and

between-day (Ferber et al., 2002). The authors suggest that GRF data sets itself apart from kinematic and kinetic measures with its high between-day consistency, likely due to the GRF being independent of marker placement (Ferber et al., 2002). Despite its high level of consistency, GRF data does not provide direct insight into the pattern of motion at each joint and plane in the way that joint kinematic measures do. While the GRF data can be used to interpret joint kinetics, these values have shown to be less consistent than kinematic measurements, and may be difficult to convey to a patient in a clinical setting (Ferber et al., 2002). Therefore, gait kinematics are more capable of providing information specific to each joint and plane with relatively consistent measurements, compared to GRF and kinetic variables

Another key finding of the early research done by Kadaba et al. (1989) shows sagittal plane kinematics are more consistent, both within- and between-day, than the frontal or transverse plane. The relative inconsistency in the frontal and transverse plane poses a considerable limitation to the work by Winter et al. (1984) as the author was restricted to collecting data in the sagittal plane. Winter et al. (1984) reported high levels of consistency for within- and between-subject kinematics, however the author did not account for frontal or transverse plane kinematics. Increased gait kinematic consistency in the sagittal plane as compared to the frontal or transverse planes has been confirmed by subsequent research, for both walking and running (Carson, Harrington, Thompson, O'Connor, & Theologis, 2001; Ferber et al., 2002; Groen, Geurts, Nienhuis, & Duysens, 2012; Steinwender et al., 2000; Szczerbik & Kalinowska, 2011)

In terms of gait kinematic measurements, prior research has shown data collected within-day to be more consistent than between-day using various protocols, statistical methods, and for both walking and running data (Carson et al., 2001; Ferber et al., 2002; Growney, Meglan,

Johnson, Cahalan, & An, 1997; Kadaba et al., 1989; Leardini, Benedetti, Catani, Simoncini, & Giannini, 1999; Tsushima, Morris, & McGinley, 2003). For a between-day comparison of gait kinematic data, there are likely multiple sources of error contributing to the reduced consistency, including both intrinsic (eg. within-subject error) and extrinsic sources (eg. between-day, between-examiner, or between-laboratory errors) (McGinley, Baker, Wolfe, & Morris, 2009). McGinley et al. (2009) note that it is natural for an individual to display slight inconsistency between days, and that within-subject error is intrinsic in nature. The authors continue by stating that within-subject error is independent to the methodology used, and cannot be reduced. However, it has been confirmed that within-subject error contributes minimally to the overall inconsistency of between-day gait kinematics, suggesting that marker placement deviations play a much larger role (Gorton et al., 2009).

In a between-day comparison of gait kinematic data, multiple examiners may be responsible for locating anatomical landmarks and placing markers. Incorporating multiple examiners can introduce another potential source of inconsistency, between-examiner error, which has been well-documented in the literature to date. Gorton et al. (2009) indicated that kinematic data collected by multiple examiners is especially susceptible to marker placement deviations. Differences in landmark identification, experience level, and methodological habits can contribute to reduced consistency of the data collected by multiple examiners at multiple sites. Marker locations recorded by the motion capture software allow for the determination of virtual joint centres, and a subsequent joint coordinate system (JCS) for each joint of interest (Cole, Nigg, Ronsky, & Yeadon, 1993). Slight deviations in marker placement alter the orientation of the JCS about which the angular displacement of each segments is calculated, leading to inconsistent joint angle measurements. The findings of Gorton et al. (2009) are in

agreement with previous studies showing the combination of between-examiner and between-day deviations in marker placement plays a critical role in the consistency of resulting data (Chambers & Goode, 1996; Della Croce, Leardini, Chiari, & Cappozzo, 2005; McGinley et al., 2009).

Recent literature shows the effect that marker placement deviation has on downstream variables of interest. Acknowledging the role of marker placement on gait kinematic consistency is crucial, however it is just as important to understand the direct relationship between the amount of placement deviation and the magnitude of resulting error. Manually misplacing markers in a systematic fashion led to errors of up to 25° relative to the ideal placement location for both Szczerbik & Kalinowska (2011) and Groen et al. (2012). Szczerbik & Kalinowska (2011) isolated their marker misplacement to the lateral knee marker, and moved the marker in a circle, with 14mm radius to the ideal placement, at 45° increments. The largest errors were observed at the hip and ankle transverse plane (Szczerbik & Kalinowska, 2011). Groen et al. (2012) manually misplaced markers at the knee, shank, and anterior superior iliac spine in either the anterior or vertical direction by a standard distance of 10mm. The authors used two different models for generating joint centres, however neither was capable of compensating for the effect of marker placement deviation (Groen et al., 2012).

As part of a larger study, Osis, Hettinga, Macdonald, & Ferber (2016) used an expansive database of healthy, uninjured runners ($n = 411$) to simulate random marker placement deviations computationally. Markers coordinates were deviated between -30mm and 30mm in the anteroposterior (AP), and vertical directions. The effect on the downstream joint kinematics was normalized to 10mm, equal to the width of the base of one marker. Up to 7.59° per 10mm of kinematic change was recorded at the ankle transverse plane, due to AP deviation of the

lateral malleolus marker (Osis, Hettinga, Macdonald, & Ferber, 2016). The next largest values of kinematic change were observed at the knee transverse, knee frontal, and hip transverse plane. Similar to Groen et al. (2012), marker placement deviation in the AP direction resulted in the largest kinematic change relative to the original placement. Considering that McGinley et al. (2009) state error in gait kinematics of 2° - 5° should be interpreted with caution, the results from simulated marker placement studies are cause for concern.

Many researchers have devised standard protocols and novel devices to improve marker placement consistency. In general, both standard protocols and marker placement devices have shown considerable success in clinical (Gorton et al., 2009) and laboratory settings (Kalkum, van Drongelen, Mussler, Wolf, & Kuni, 2016; Noehren, Manal, & Davis, 2010; Telfer et al., 2010). Gorton et al. (2009) implemented a standard gait assessment protocol as part of a larger study focusing on various sources of error and their relative contribution to the overall error between multiple partner clinics. A single individual visited 12 clinics and underwent a gait analysis carried out by two local examiners according to each clinic's current protocol. Over the following year, a standard gait assessment protocol was implemented across all clinics. The standardization process consisted of training videos that focused on landmark identification and marker placement, as well as an in-person instructional session attended by all examiners (Gorton et al., 2009). The same individual then returned to all 12 clinics and the gait analysis procedure was repeated. Following implementation of the standard protocol, the authors reported more consistency in the downstream gait variables collected between clinics. While these results were encouraging, the improved consistency was not seen for all joint angles, and for some joint angles the consistency was reduced after introducing the standard protocol (Gorton et al., 2009). A limitation of the standard protocol and training sessions is that it does

not provide continual feedback to the examiner in real-time. It is unknown whether the improvements would still be seen upon a second follow-up session, or if the examiners would trend back towards their original habits in marker placement and the greater inconsistency between clinics.

Other attempts at improving marker placement consistency have involved the use of novel devices (Kalkum et al., 2016; Noehren et al., 2010; Telfer et al., 2010). The design of the marker placement devices varies, from an apparatus that uses adjustable arms to position laser pointers to a bent plastic wire with markers stacked along its length. Regardless of the exact methodology, the use of a marker placement device has shown to effectively increase the consistency of downstream gait kinematic variables by way of reducing marker placement deviation (Kalkum et al., 2016; Noehren et al., 2010; Telfer et al., 2010). However, the devices accomplish this by replicating a previously recorded marker position, and are therefore entirely dependent on the initial, or baseline, marker placement. Another limitation is the added time required to set-up and operate the device (Noehren et al., 2010).

Previous literature shows that marker placement consistency can be improved, and that there is a positive effect on the resulting gait kinematics, however the limitations of current protocols and devices must be addressed. More recently, a real-time feedback software tool has been developed with the aim of improving marker placement consistency by referencing a large database ($n = 340$) of previously collected static trials (Osis, Hettinga, Macdonald, & Ferber, 2014). Marker placement for each of the 340 static trials were completed by a single expert examiner, with over 14 years of experience in clinical anatomy, making this database a ‘gold standard’ (Osis et al., 2014). Briefly, the marker position data for all 340 static trials are normalized, and the current static trial is compared to a subset of trials that are most anatomically

similar based on all marker coordinates (Osis et al., 2014). Within seconds of collecting the current static trial, the examiner receives feedback in the form of a three-dimensional (3D) plot showing their marker placement locations compared to those expected by the software. The feedback tool provides the examiner with a visual reference for potentially erroneous marker placements and the opportunity to adjust the markers as they see fit before proceeding with dynamic trials.

Preliminary research using the real-time feedback tool has shown promising results (Osis et al., 2016). As mentioned previously, the authors used the software tool to simulate marker misplacements and determine the direct effect of marker misplacement on resulting kinematic variables (Osis et al., 2016). Ankle, knee, and hip kinematics in the transverse plane, as well as knee and hip kinematics in the frontal plane were found to be most sensitive to placement inconsistency. In addition, novice examiners with anatomical knowledge, but no biomechanical experience, visited the laboratory and performed marker placements on a single runner with and without real-time feedback. On the same day, the expert performed a static trial collection. Following all static trials, the single runner completed a running trial. Gait kinematic data were analyzed using each pair of novice static trials and the expert static trial then specific variables were compared for consistency. The researchers reported median deviation of resulting kinematic variables between six novice users and one expert user trending towards zero (Osis et al., 2016). With data collection restricted to a single day, the protocol did not allow for between-day comparisons, and while the preliminary results were encouraging the outcomes are limited by the small sample size ($n = 6$). Therefore, further research is necessary to understand the role of real-time marker placement feedback, and its ability to improve marker placement consistency among novice examiners over multiple data collections.

1.2 Purpose

The purpose of the current study was to improve consistency of anatomical marker placement by using methods that improve upon previous attempts at standard protocols and placement devices by providing real-time feedback.

1.3 Objectives

The study objective was to build on the preliminary work of Osis et al. (2016) to determine if the use of real-time feedback software is capable of improving marker placement consistency (decreased 95% confidence interval range) for a group of novice examiners, and determine the effectiveness of the real-time feedback software across multiple days by conducting a one-week follow-up session. In addition, we attempted to confirm the results of Osis et al. (2016) showing which joint angles are most sensitive to marker placement deviations.

To accomplish these objectives, we calculated the resulting 3D gait kinematics at the ankle, knee, and hip for each of the novice examiners and compared these mean values across static trial conditions, pre- and post-feedback.

1.4 Hypotheses

In accordance with previous literature, we hypothesized that trials collected post-feedback would lead to improved consistency compared to trials collected before receiving feedback, and that this improvement in consistency would be represented by a reduced 95% CI range. Still following the results of Osis et al. (2016), we hypothesized the ankle transverse, knee frontal, knee transverse, hip frontal, and hip transverse plane would show the greatest reduction in 95% confidence interval (CI) range. The mean joint angle, about which the 95% CI

was calculated, was not expected to differ between conditions as this was more representative of the runner's intrinsic consistency from one data collection to the next.

CHAPTER TWO: REVIEW OF THE LITERATURE

2.1 Gait Kinematics

Biomechanics is defined as the study of forces acting upon and a within a biological structure, and the effects of those forces on the structure (Hay, 1973). To go one step further, *kinetics* refers to the internal and external forces themselves, meanwhile *kinematics* describes the resulting effects of those forces on the biological structure. For decades, researchers have sought to understand the kinematics of human locomotion, or gait. By quantifying these movement patterns researchers can begin to objectively distinguish normal and abnormal gait kinematics. From a clinical standpoint, finding methods to describe an individual's gait can play an important role in understanding the effects of certain joint pathologies, chronic diseases, and neurological disorders (Beaulieu, Lamontagne, & Beaulieu, 2010; Ferber et al., 2002; Gorton et al., 2009). Additionally, gait analysis can be used by coaches and trainers as a means of improving athletic performance (Ford, Myer, & Hewett, 2007).

2.1.1 Methods for Collecting Kinematic Data

Early methods for quantifying human gait kinematics relied upon the human eye to make observations. A film camera, or *cine camera*, used rolls of film and had mechanism for holding the film stationary at a constant time interval known to the researcher. The film would be exposed during this short time interval, and the image of the subject recorded. Data collection required placement of stickers, paint, or reflective markers at specific points of interest on the subject's skin (Nigg & Herzog, 2006). As part of a very time intensive process, researchers analyzed each frame of film individually, leading to considerable delay in analyzing the data. In response, Winter et al. (1972), developed a method for digitizing the marker data that reduced the time required for analysis. By incorporating a television recording of the subject, the marker

locations could be processed to yield marker coordinates in an absolute reference frame (Winter, Greenlaw, & Hobson, 1972). Winter's (1972) digitizing method drastically reduced the time required to analyze the segment position and joint kinematic data, however, hours of analysis were still required for one trial.

The impracticality of purchasing expensive film, the need to replace film during data collection sessions, and the time intensive analysis were the catalysts for the development of video camera techniques (Nigg & Herzog, 2006). Initially, the video camera used the same basic principles as the film camera, however the use of video reduced the cost of materials, increased the length of time that data could be collected for, and eventually allowed for increased sampling frequency. Advances in computational techniques that occurred throughout the decades that followed led to motion capture technologies that improved upon the limitations of those that came before. These advancements have yielded the gold standard for kinematic gait analysis; the use of multiple high speed video cameras that track the motion of retroreflective markers fixed to specific anatomical landmarks on the subject's body.

The current gold standard motion capture systems use active cameras to track passive markers. The high-speed cameras are responsible for both emitting infrared light and for sensing light that is reflected off the markers. By sensing the angle of light returning to the cameras, the corresponding software uses that information to determine the location of each marker within the capture volume. Capable of sampling motion data at up to 250Hz, current high speed cameras can be adapted to collect motion capture data for a variety of biological phenomena. A single camera is only capable of collecting data in two-dimensions (2D), and for basic movements, 2D may be appropriate. However, by incorporating multiple cameras, each collecting a 2D image simultaneously, the 3D coordinates can be determined using the direct linear transformation

(DLT) method proposed by Abdel-Aziz & Karara (1971). The DLT method provides a linear relationship between the 2D coordinates of each marker corresponding to the 2D image that is collected by each camera, and the 3D coordinates of that marker in the capture space (Abdel-Aziz & Karara, 1971). For the determination of a marker's 3D coordinates, the DLT requires that the marker can be seen by a minimum of two cameras. In a practical setting, it is common for a marker to be lost by one or more cameras depending on the movement being captured (Nigg & Herzog, 2006). Therefore, to ensure all markers are being tracked throughout, a data collection protocol may require up to six or more cameras to provide sufficient marker coordinate information to calculate the joint kinematics of interest.

2.1.2 Segment Coordinate System

To provide anatomical or clinical context to the marker location data collected by the cameras, the marker positions must be considered as a system of rigid body segments. The common segments of interest when considering lower body gait kinematics are the pelvis, thigh, shank, and foot. The position and orientation of a segment can be used to determine its movement relative to any adjacent segment (Nigg & Herzog, 2006). By assuming all segments to be rigid bodies, a segment coordinate system (SCS) can then define a constant orientation of any point along that segment. The SCS is defined using a minimum of three markers fixed to the segment of interest. By fixing the markers to a rigid shell that is fastened to the segment, the relative marker error is reduced when calculating segment kinematics (Manal, McClay, Stanhope, Richards, & Galinat, 2000; Nigg & Herzog, 2006). Therefore, when tracking the coordinates of these markers, the orientation of each segment can be determined relative to its adjacent segments.

2.1.3 Joint Coordinate System

Adjacent segments rotate and orient themselves relative to one another at a joint. When considering the pelvis, thigh, shank, and foot to be segments of interest, the primary joints of interest are defined at the hip, knee, and ankle. To describe the joint kinematics at either the hip, knee, or ankle one must be able to quantify the position and orientation of the adjacent segments relative to one another. The relative position of one segment to another, often the distal segment in relation to the proximal segment, can be obtained through an ordered sequence of rotations about defined axes (Cole et al., 1993). The first proposal of a body fixed JCS involved the predefinition of one joint axis fixed in the proximal segment, a second axis in the distal segment, and a third axis normal to the first and second axes (Grood & Suntay, 1983). By predefining the rotation sequence, the authors improved upon prior methods. However, the new JCS was only designed for the knee joint, and was limited by its inability to be applied in a standardized manner to other joints (Cole et al., 1993). In addition, as noted by Cole et al. (1993), while clearly defining the rotation sequence, the JCS defined by Grood & Suntay (1983) did not strictly define the selection of each specific joint axis. Therefore, little agreement existed among research groups as to which set of axes should be used to determine the relative position and orientation of the segments.

Cole et al. (1993) showed that for two different definitions of the proposed JCS, the differences in the resulting joint rotations were substantial for walking and running, and were even larger for increased ranges of motion. In response, Cole et al. (1993) developed a standardization of the JCS. The standard JCS built upon the work of Grood & Suntay (1983), and defined a standard JCS that could be applied in a general sense to any joint (Cole et al., 1993). The standard JCS defined the *flexion axis* as the axis of the proximal segment that is

oriented predominantly in the mediolateral direction, the *longitudinal axis* as the axis oriented lengthwise along the distal segment, and the *third axis* defined as the cross-product of the *flexion axis* and *longitudinal axis* (Figure 2-1).

Figure 2-1: The joint coordinate system as defined by Cole et al. 1993 with permission

2.1.4 Static Trial

The placement of retroreflective markers on specific anatomical landmarks allows for the definition of the hip, knee, and ankle joint axes. Axis definition is accomplished during a static trial in which the subject stands in a neutral, anatomical position. The cameras also record the position and orientation of the segment coordinate systems in relation to the adjacent JCS. By

collecting a static trial, the examiners can afford to remove the anatomical landmarks for the dynamic trial, as the segment coordinate data from the dynamic trial can be compared to the measured position and orientation from the static trial (Nigg & Herzog, 2006).

2.2 Consistency of Gait Kinematic Data

As 3DGA becomes more popular in a clinical and laboratory setting, many research groups have become invested in determining the consistency of the resulting kinematic data. Even prior to 3D motion capture, Winter (1984) provided one of the first assessments of the consistency of human locomotion between- and within subjects. The author designed a protocol to measure the consistency of kinematic and kinetic parameters associated with walking gait using a 16mm film camera to track sagittal plane motion. One subject took part in nine similar walking trials, at their natural cadence, spaced evenly over the course of three days. The resulting joint angles at the hip, knee, and ankle were consistent along with the overall GRF (Winter, 1984). For all nine trials, the coefficient of variation (CV), equal to the ratio of the standard deviation to the mean, for the ankle, knee, and hip was 9%, 10%, and 19% respectively. In comparison, the joint moments were considerably less consistent, with the knee (67%), and hip (72%) showing the least consistency throughout the stride (Winter, 1984). For the authors' investigation into between-subject consistency, subjects were separated into three different cadence groups: slow, natural, and fast. As a result, consistency improved as a group with increasing cadence, however the between-subject consistency remained lower than the within-subject consistency for all three joints (Winter, 1984). However, the author was limited by only collecting kinematic data in the sagittal plane, which subsequent research would show to be more consistent than the frontal or transverse planes (Growney et al., 1997; Kadaba et al., 1989; McGinley et al., 2009). Being unable to collect in all three planes of motion limits the validity of

the results as potential kinematic variability in the frontal and transverse planes is not accounted for. In addition, while standard at the time, the sampling rate of 50Hz contains much less information than current motion capture capabilities of up to 250Hz. The findings by Winter (1984) provided necessary insight to the consistency of an individual's walking gait, incorporating both kinematic and kinetic data, however advancements in motion capture technology allowed subsequent research to explore the concept of gait consistency even further.

2.2.1 Between- and Within-Day

Winter (1984) suggested joint kinematics of walking are more consistent within-subject than the corresponding joint kinetics, and that a single individual's joint kinematics are more consistent than between-subject measurements. The first to address within- and between-day kinematic consistency did so using methods that allowed for motion tracking in the sagittal, frontal, and transverse plane (Kadaba et al., 1989). During this time, the use of computer-aided motion capture was slow to gain popularity in the clinical biomechanics community. The authors point to the general uncertainty among researchers and clinicians as to whether gait kinematic data collected on one particular day was representative of that individual's typical walking pattern (Kadaba et al., 1989). For meaningful clinical decisions to be made, the kinematic data that is collected must be consistent enough from one day to the next. By using five infrared cameras (sampling rate of 50Hz) the authors collected kinematic data using 3DGA for 40 subjects walking over ground along a six-metre walkway. Three trials were collected on each of three days, with at least one week occurring between days (Kadaba et al., 1989). Subjects were instructed to walk at a self-selected speed for all trials. In addition to gait kinematics, Kadaba et al. (1989) also collected kinetic data using two force plates along the walkway, as well as electromyographic data using surface electrodes.

To determine the consistency of the spatio-temporal gait parameters, CV was calculated both within- and between-day. To compare the waveform data as a function of the gait cycle, Kadaba et al. (1989) introduced the coefficient of multiple correlations (CMC). The CMC provides an index, from 0 to 1, that indicates the similarity of the shape of waveforms. Similar waveforms will trend towards a value of 1, while dissimilar waveforms will trend towards 0 (Kadaba et al., 1989). Using CMC as the primary form of analysis the authors concluded that consistency of gait kinematics at the hip, knee, and ankle in the sagittal plane was excellent both within- (> 0.975), and between-day (> 0.933). While gait kinematics in the frontal and transverse plane showed good consistency within-day, the between-day consistency was significantly lower in these planes (Kadaba et al., 1989). The authors identified a constant offset when considering the joint kinematic waveforms from between-days, which was attributed to slight misplacement of the anatomical markers from one day to the next. With the offset accounted for, the between-day consistency improved across all joints in each plane, however it remained significantly less than consistent than data collected within-day.

Following the preliminary work by Kadaba et al. (1989), others have confirmed within-day consistency to be greater than between-day, using a variety of protocols and statistical measures (Carson et al., 2001; Ferber et al., 2002; Leardini et al., 1999).. For instance, both Leardini et al. (1999) and Carson et al. (2001) found that their proposed protocols for determining the multi-joint kinematics of the foot and ankle during level, over ground walking showed greater within-day consistency as compared to the between-day condition. Leardini et al. (1999) also used the CMC, however Carson et al. (2001) came to the same conclusion by calculating 95% CI of the difference between any two conditions. As the first to analyze within- and between-day consistency of over ground running trials, Ferber et al. (2002) utilized the ICC

along with 95% CI data to show significantly improved kinematic consistency within-day compared to between-day for the running stride. An ICC trending towards 1 represents perfect correlation, while an ICC trending towards 0 signifies no correlation.

The presence of a waveform offset in kinematic data collected between-days, due to inconsistencies in marker placement was also noted in subsequent research (Carson et al., 2001; Ferber et al., 2002; Leardini et al., 1999). Reduction of the offset was proposed by subtracting out a neutral position, obtained during the static trial (Carson et al., 2001). Ferber et al. (2002) went an additional step by hypothesizing the offset would have a larger effect on absolute measures such as peak joint angles than it would on relative measures such as joint excursion or angular velocity, resulting in reduced consistency for peak joint angles. Contrary to the hypothesis, the results showed that both absolute and relative measures exhibited moderate to high intraclass correlation coefficients (ICC values > 0.82) in a within-day comparison (Ferber et al., 2002). However, the between-day comparison showed that for the absolute measure of peak joint angle, the ICC for five out of nine peak angles was below 0.72 as compared to one joint excursion and one angular velocity variable (Ferber et al., 2002).

The work of multiple research groups showed an individual's within-day gait kinematics were more consistent than between-day for both walking and running, and for multiple joint locations and coordinate systems. It was also indicated that relative measures of gait are more consistent than absolute measures in a between-day comparison. The inconsistency of between-day kinematics is especially concerning for clinical or research applications that require interpretation of baseline and follow-up kinematic data. Beyond understanding differences in gait kinematic consistency within- and between-days, it is critical for examiners to be aware of how consistency might differ among the three planes of motion. Being aware of differences in

sagittal, frontal, and transverse plane consistency may help an examiner decide which outcome variables can be relied upon for analysis.

2.2.2 Sagittal, Frontal, and Transverse Planes

As mentioned previously, the work done by Kadaba et al. (1989) to determine the consistency of within- and between-day gait kinematics was also the first to collect kinematics in all three planes of motion: sagittal, frontal, and transverse. The authors found that sagittal plane kinematics showed greater consistency than frontal or transverse plane, for both within- and between-day conditions (Kadaba et al., 1989). The relatively low consistency of frontal and transverse plane kinematics was supported in subsequent literature, suggesting that care must be taken when coming to conclusions regarding gait kinematic data in the frontal or transverse plane (Carson et al., 2001; Ferber et al., 2002; Groen et al., 2012; Steinwender et al., 2000; Szczerbik & Kalinowska, 2011). Research into permanent movement disorders such as cerebral palsy (CP) found that gait kinematic consistency was slightly higher for the control children, on average (Steinwender et al., 2000). However, in both the CP and control case, sagittal plane kinematics at the hip, knee, and ankle showed the highest consistency, in agreement with the literature surrounding healthy populations. The work of Steinwender et al. (2000) shows the high consistency of kinematics in the sagittal plane relative to the frontal and transverse planes is independent of the protocol or statistical analysis that is used.

2.3 Error in Gait Kinematics

With the consistency of gait kinematic data well documented, researchers became aware of the limitations of baseline and follow-up investigations due to the relatively large inconsistencies of between-day gait kinematics. However, research protocols that track changes to an individual's gait kinematics over time are necessary from both a clinical and research perspective. For example, analyzing an individual's gait before and after an intervention allows the examiner to draw potential conclusions regarding the effectiveness of the intervention for that individual. Therefore, it is unrealistic to cease analysis of between-day comparisons, and instead the limitations of these studies must be addressed. For future research to address any inconsistency, or at the very least account for it in the methodology, the sources of error that cause the inconsistency must be determined, and clearly defined.

2.3.1 *Within-Subject*

It is natural for a single individual to show kinematic inconsistency even within the same test day (McGinley et al., 2009). Also referred to as intra-subject or inter-trial error, this cannot be reduced and is intrinsic to the measurement, meaning that it is independent of methodological errors (Schwartz, Trost, & Werve, 2004). Fortunately, research attempting to discern within-subject error has either shown high consistency for inter-trial comparisons (Tsushima et al., 2003) or has shown this error to be inconsequential (Gorton et al., 2009; Schwartz et al., 2004).

Tsushima et al. (2003) measured the consistency of joint kinematics for six healthy subjects using a repeated measures design. Each subject's walking gait was analyzed over ground by two different testers, on two different days, with five trials collected on each day. The authors determined the within-subject consistency by comparing the five trials collected on one

day, without removal of markers (Tsushima et al., 2003). On average, for all six subjects left and right limbs, the lowest reported CMC value for the within-subject condition was 0.857 for knee transverse plane. For each joint angle, the within-subject CMC value was higher than both the between-day and between-tester condition (Tsushima et al., 2003).

Similar to Tsushima et al. (2003), Gorton collected five trials to determine within-subject error over the course of one test day, and took one step further by attempting to standardize the marker placement between days (Gorton et al., 2009). As part of larger study examining the multiple sources of error in kinematic gait analysis, Gorton et al. (2009) collected over ground walking data on a single subject over six consecutive days. Five trials were collected each day, and the marker locations were indicated using permanent ink in order to guide placement for the following day (Gorton et al., 2009). For each of the six days, the authors calculated the mean joint angle of all five trials. An analysis of variance (ANOVA) with trial as a fixed factor showed no within-subject difference between-trials. In addition, the authors performed an ANOVA with day as a fixed factor which showed that five out of eight joint angles were different between days, despite attempts to standardize marker location with permanent ink (Gorton et al., 2009). Although the results may suggest within-subject differences across days, the authors emphasize the possibility that minor differences in alignment were present. It is also noted that despite the significant findings, the within-subject error seen across days was very low in magnitude compared to the overall error (Gorton et al., 2009).

2.3.2 System Calibration

Gorton et al. (2009) was the first to explicitly report the error of system calibration as it pertains to overall kinematic inconsistency. The authors determined the calibration error

associated with multiple clinic or laboratory locations by moving an instrumented rod through the capture volume at each of 12 partner laboratories. The rod was instrumented with markers to simulate a right foot, shank, thigh and pelvis (Gorton et al., 2009). Only data from seven locations were suitable for analysis, and these seven locations showed high levels of consistency as the average standard deviation for all joint angles measured was 0.5° across locations. Gorton et al. (2009) show that a properly configured and calibrated motion capture system contributes negligible error even for a multi-centre collaboration, and confirm the assumptions of previous research (Chambers & Goode, 1996) (Figure 2-2).

2.3.3 Between-Examiner (Interpretation Error)

Between-examiner error can present itself within kinematic gait analysis in multiple ways. One example is the observer bias that may exist when analyzing gait analysis data. Especially in a clinical setting, between-examiner error can potentially lead to misguided diagnosis and improper treatment protocols. The ability of an examiner to analyze and assess gait comes with experience, however Skaggs et al. (2000) report significant inconsistency in diagnosis and treatment recommendations between experienced clinicians. Gait assessment data from seven children that underwent testing at a single laboratory were provided to 12 examiners from six institutions. The examiners were instructed to identify soft-tissue and bony abnormalities as well as provide treatment recommendations for whatever abnormalities were observed (Skaggs et al., 2000). The authors used kappa statistics to analyze the level of agreement among examiner responses. The kappa coefficient accounted for chance agreement by assigning a value of 1.0 for perfect agreement, and a value of 0 for chance agreement. In addition, the kappa coefficient was not reported for examiner responses that were rarely given as this was more likely a reflection of misinterpretation and if most examiners did not respond in

the same way the kappa coefficient would trend towards 1.0 (Skaggs et al., 2000). The results indicated fair or slight levels of agreement for the recommendation of all bone surgical procedures. Of the procedures that were recommended at least 5% of the time, 0.22 was the largest kappa coefficient recorded (Skaggs et al., 2000). The authors concluded that the treatment recommendation for bony abnormalities was largely dependent on the clinic that the responders belonged to. The findings by Skaggs et al. (2000) suggest that small inconsistencies in gait kinematic data can be exacerbated by individual bias and further inconsistency when examiners attempt to diagnose and determine treatment.

2.3.4 Between-Examiner (Marker Placement Error)

One of the major strengths of the work by Gorton et al. (2009) was the authors' ability to distinguish different sources of error. Further, the authors presented each source of error as separate components of the overall error in gait kinematic analysis. With the purpose of assessing the magnitude and source of error between multiple laboratories, a single subject visited 12 partnered gait analysis laboratories over the course of a three-month period. Ten gait analysis trials were performed at each site by two examiners. The mean joint angles pertaining to all 24 examiners were calculated in the sagittal plane at the pelvis, hip, knee, and ankle, as well as in the frontal plane for the pelvis and hip, and the transverse plane for the pelvis, hip, and ankle (Gorton et al., 2009). The mean joint angles were then averaged across all 24 examiners, and the standard deviation (s) was used to represent the overall error between sites at each joint parameter. The error between sites ranged from 1.2° for the pelvis frontal plane to 7.3° in the hip transverse plane. Based on the authors methodology, the largest error attributed to within-subject error was $s = 1.5^\circ$. Using the instrumented rod to determine system calibration error between sites, the largest reported error was $s = 0.7^\circ$ (Gorton et al., 2009). At the level of each

joint parameter, Gorton et al. (2009) used the variance (s^2) to determine the relative proportion of within-subject, between-session, and system calibration error in terms of the overall error between sites. The authors discovered that more than 75% of the overall error could not be attributed to any of the above sources for all but two joint parameters (Gorton et al., 2009). Having accounted for all other sources, between-examiner error in the form of marker placement inconsistency contributes up to 75% of the total error in gait analysis (Gorton et al., 2009) (Figure 2-2).

Measurement - 145°

Between-Examiner: 18.4°

System Calibration: 1.4°

Within-Subject: 1.8°

Figure 2-2: Diagram showing the relative contribution of various sources of error as reported by Gorton et al. 2009.

Gorton et al. (2009) acknowledge that while the subject walked at a self-selected, natural pace for all assessments, the pace was not necessarily the same at each site. It is possible that

even slight differences in walking velocity could influence gait variability (Jordan, Challis, & Newell, 2007), which was unaccounted for, and a potential source of error. However, the authors suggested that the use of a metronome to maintain constant velocity would have created a less natural walking pattern, perhaps adding to the inconsistency between sites (Gorton et al., 2009)

The conclusion that marker placement deviations between-examiner and between-session play a critical role in gait kinematic inconsistency echoes what other groups have previously speculated (Chambers & Goode, 1996; Della Croce et al., 2005; McGinley et al., 2009). An early assessment of between-examiner error was completed by Chambers & Goode (1996), in an effort to determine the feasibility of multi-centre collaboration. The authors hypothesized that inconsistency between gait measures at multiple sites was due largely to a combination of 1) marker placement deviations, and 2) within-subject error (Chambers & Goode, 1996). A single subject was analyzed at five sites, with markers placed and all measurements made by the local clinician according to the manner used at that clinic. A sixth examiner travelled with the subject to each location and placed markers in a consistent manner for a secondary gait assessment (Chambers & Goode, 1996). To reduce error due to differences in system set-up, a test jig was utilized to ensure consistency in the system calibration at all five clinics, and the results indicated no significant differences (Chambers & Goode, 1996). The results of the study, and any inconsistencies between clinics depended on which joint was being analyzed during which phase. Statistical analysis using multivariate Hotelling's T^2 showed significant differences ($p < 0.05$) in the sagittal plane hip and knee kinematics during swing phase between the five clinics, but no difference during stance (Chambers & Goode, 1996). However, sagittal plane kinematics at the ankle were shown to vary considerably through both stance and swing phase. The authors

concluded that while statistical differences in the sagittal plane gait kinematics occurred between clinics, and that these were attributable to marker placement deviations, the inconsistencies weren't clinically significant (Chambers & Goode, 1996). It is important to consider that these findings are limited to gait kinematics in the sagittal plane. Considering that previous research has shown the sagittal plane to be the most consistent within- and between-sessions (Carson et al., 2001; Ferber et al., 2002; Kadaba et al., 1989), it is possible that Chambers & Goode (1996) overlooked clinically significant differences in the frontal and transverse planes between clinics. Despite not accounting for frontal or transverse plane kinematics, the authors provided the groundwork for subsequent investigations into between-examiner error.

More recently, systematic reviews of the literature surrounding the consistency of kinematic gait measurements have further acknowledged the role of marker placement deviation and differences in landmark identification between-examiners (Della Croce et al., 2005; McGinley et al., 2009). McGinley et al. (2009) suggest that continual modifications must be made to measurement techniques to reduce levels of inconsistency, and that deviations in marker placement are the principal source of between-examiner error. The studies explored in a systematic review of literature by Della Croce et al. (2005) repeatedly showed that consistency of the kinematic gait data, and its interpretability, is highly dependent on the determination of the JCS, by way of anatomical landmark identification and marker placement.

2.4 Effect of Marker Placement Deviation on Resulting Kinematics

The literature surrounding gait kinematics has documented various sources of error contributing to inconsistency in the data, and the magnitude of such error. Additional research identified deviations in marker placement as the largest contributor to the inconsistencies (Chambers & Goode, 1996; Della Croce et al., 2005; Gorton et al., 2009; McGinley et al., 2009).

However, the direct relationship between specific marker placement deviations and the resulting kinematic measurement was still unknown. The research that followed would provide more insight to which joint kinematic parameters were most sensitive to specific marker placement deviations.

2.4.1 Manual Deviations

In particular, two groups have explored the role of marker placement deviation on joint kinematic outcomes of over ground walking by manually manipulating the marker locations during set-up (Groen et al., 2012; Szczerbik & Kalinowska, 2011). Although the methodologies for manipulating the marker placement varied, both groups found these deviations produced substantial differences in the resulting kinematic measures, most notably in the frontal and transverse planes.

Szczerbik and Kalinowska (2011) observed the effect of marker placement deviation on two subjects, each with a different knee problem affecting gait in the sagittal plane. One subject with knee hyperflexion, and the second diagnosed with CP leading to knee flexion contracture (Szczerbik & Kalinowska, 2011). Subjects walked at a self-selected pace and their gait was recorded using motion capture cameras. After the collection of a static trial with ideal marker placement, the knee marker was systematically misplaced around the left femoral epicondyle (Szczerbik & Kalinowska, 2011). Next, eight iterations of marker deviation took place, each one followed by six walking trials. To begin each session the marker was moved 14mm from the ideal position, equal to the diameter of one marker. For the subsequent sessions the marker was adjusted by 45°, in a circle with radius 14mm relative to the ideal marker position, and a new session took place every 45° (Szczerbik & Kalinowska, 2011). The location of the other markers

was not adjusted (Szczerbik & Kalinowska, 2011). The authors analyzed the resulting mean joint kinematics of all six trials in the sagittal, frontal, and transverse plane for the pelvis, hip, knee, and ankle. The maximum difference between the ideal marker placement trial and any of the deviation trials was largest for the hip and ankle transverse plane with a range of 24° and 25° respectively (Szczerbik & Kalinowska, 2011). In addition, the authors noted the influence of marker placement deviation was consistent for both knee pathologies. The investigation was limited by incorporating only two subjects, and even further by the authors not providing statistical analysis, however the results provided insight into the relationship between marker placement deviation and gait kinematics.

Groen et al. (2012) also manipulated marker placement manually, however the authors collected data on eighteen subjects. Using Vicon motion capture cameras, Groen et al. (2012) used two different methods to determine the joint centres: (1) the standard Vicon Clinical Manager (VCM) static trial, and (2) a functional movement trial using an Optimized Lower Limb Gait Analysis (OLGA) based on the same marker set as the VCM. The VCM used marker locations during a static trial to determine joint centre locations and define a JCS, while OLGA also incorporated marker positions, it also required subject anthropometric measurements and joint range of motion trials to further optimize the joint centre location (Groen et al., 2012). All data for one subject was collected in a single day, consisting of six sessions, each with ten over-ground walking trials. The first session involved ideal marker placement, and each of the five sessions that followed involved manual marker deviation of 10mm (Groen et al., 2012). Each session involved only one of the following deviations: (1) anterior deviation of the knee marker, (2) vertical deviation of the knee marker, (3) anterior deviation of the shank marker, (4) vertical deviation of the shank marker, or (5) vertical deviation of the anterior superior iliac spine (ASIS)

marker (Groen et al., 2012). The ideal placement location was identified with permanent marker to ensure all deviations were from the same reference point. The authors calculated mean joint kinematics for each session, using the VCM and OLGA models. Next the root mean square error (RMSE) was calculated between the first session and each of the five deviations. The within-session error was also calculated using RMSE to determine the consistency of gait kinematic data from one trial to the next. On average, across all sessions, the RMSE values for the VCM model were larger than OLGA for most joint angles. However, the marker deviation sessions lead to RMSE values that exceeded the within-session RMSE, independent of the model used. Anterior deviation of the thigh, knee, and shank markers resulted in RMSE values greater than 10° and up to 25° in the frontal and transverse plane (Groen et al., 2012). With the reported RMSE values of approximately 3° or less associated with between-trial error, these inconsistencies due to marker placement deviation are substantial. In summary, while the OLGA model showed reduced RMSE for marker placement deviations, neither could fully compensate for the effect of marker placement deviation (Groen et al., 2012). The authors acknowledge the difficulty of standardizing the deviation of markers between all subjects, as the shape and structure of bony landmarks and soft tissue differs from one subject to the next. Despite using a single examiner for the placement of all markers, the RMSE values may be exacerbated by further inconsistency in the re-application of markers by the examiner (Groen et al., 2012). The authors show that consistent marker placement is critical for both models, and that the resulting inconsistency in joint kinematic data exceeds the between-trial inconsistency.

2.4.2 Simulated Deviations

Groen et al. (2012) acknowledged that simulating marker deviations computationally would have improved the consistency in actual deviations between subjects. As part of a larger

investigation, Osis, Hettinga, Macdonald, and Ferber (2016) applied a simulation to a database of 411 subjects to quantify the relationship between marker placement deviations and downstream kinematic variables for a treadmill running trial. The marker placements for all 411 subjects were completed by the same examiner with 15 years of experience in clinical anatomy. Twenty-nine static trials were created for each subject: one unaltered trial, and twenty-eight simulated marker deviations (Osis et al., 2016). Each trial involved a deviation in either the AP, or vertical direction (bilaterally) to one of the following marker locations: greater trochanter, medial and lateral knee, medial and lateral malleolus, and medial and lateral metatarsophalangeal joints. The magnitude of deviation was randomly assigned, between $\pm 30\text{mm}$ (Osis et al., 2016). Joint kinematics for the running trial belonging to each subject were calculated using each of the 29 static trials. The authors defined the kinematic change as the absolute difference in joint kinematic variables of the unaltered static trial to the altered trials. To compare the sensitivity to marker placement deviation between joint angles, the kinematic change was standardized to a 10mm placement deviation, which is approximately the width of one marker (Osis et al., 2016). Four-hundred and eleven values for kinematic change, standardized to a deviation of 10mm, were calculated for each joint kinematic variable. The 95th percentile of these values represented a near-worst-case scenario, and this value was recorded by the authors. The entire simulation was repeated 10 times, and the average 95th percentile of kinematic change was reported in the results (Osis et al., 2016).

Osis et al. (2016) found AP deviations resulted in the largest values of kinematic change per 10mm, most notably in the transverse plane, similar to Groen et al. (2012). In keeping with previous literature, the vertical deviations also showed very little effect on resulting joint kinematic variables in any of the three planes of motion (Osis et al., 2016). The largest values

for kinematic change were associated with the ankle transverse ($7.59^{\circ}/10\text{mm}$ AP deviation of lateral malleolus marker), knee transverse ($6.49^{\circ}/10\text{mm}$ AP deviation of medial malleolus marker, and $5.51^{\circ}/10\text{mm}$ AP deviation of the medial knee marker), knee frontal ($5.16^{\circ}/10\text{mm}$ AP deviation of the medial malleolus marker), and hip transverse plane ($4.77^{\circ}/10\text{mm}$ AP deviation of lateral knee marker) (Osis et al., 2016). It must be noted that the results of the simulation emphasize a near-worst-case scenario of marker placement deviation occurring at one location, and does not necessarily reflect a real-world situation in which multiple markers may be misplaced simultaneously. However, the findings are substantial considering that errors in gait kinematics of $2\text{-}5^{\circ}$ should be interpreted with caution, and error greater than 5° is sufficient to cause misdiagnosis in a clinical setting (McGinley et al., 2009). While the variety of study protocols and subject demographics make it difficult to compare studies directly, many studies report gait kinematic error in ranges of $2\text{-}5^{\circ}$ and greater, especially in the frontal and transverse planes (Figure 2-3).

Figure 2-3 (a): Summary of literature that report 3DGA errors at the ankle joint in standard deviation (SD), standard error (SE), or root mean square error (RMSE). Error is reported in degrees (deg) *adapted from McGinley et al. 2009.*

Figure 2-3 (b): Summary of literature that report 3DGA errors at the knee joint in standard deviation (SD), standard error (SE), or root mean square error (RMSE). Error is reported in degrees (deg) *adapted from McGinley et al. 2009.*

Figure 2-3 (c): Summary of literature that report 3DGA errors at the hip joint in standard deviation (SD), standard error (SE), or root mean square error (RMSE). Error is reported in degrees (deg) *adapted from McGinley et al. 2009.*

Study Details: **Benedetti** – Average SD between 7 laboratories (Benedetti, Merlo, & Leardini, 2013). **Besier** – Average systematic error between-day (Besier, Sturnieks, Alderson, & Lloyd, 2003). **Charlton*** - Average SD between-examiner using functional (blue) and manual methods (red) (Charlton, Tate, Smyth, & Roren, 2004). **Gorton** – SD between-examiners at multiple laboratories before (green) and after (blue) standard protocol implementation (Gorton et al., 2009). **Groen** – Average RMSE following simulated marker placement deviation using functional (red) and manual methods (green) (Groen et al., 2012). **Growney** – SD between-session (Growney et al., 1997). **Leardini** – Average SD between-examiner (Leardini et al., 2007). **Leigh*** – RMSE for within-examiner novice using functional (green) and manual methods (blue) (Leigh, Pohl, & Ferber, 2014). **Maynard** – SD between-examiners (Maynard, Bakheit, Oldham, & Freeman, 2003). **Noehren** – SE between-day without (green) and with the aid of marker placement device (blue) (Noehren et al., 2010). **Osis** – Error per 10mm of simulated marker placement deviation (Osis et al., 2016). **Pohl*** – RMSE between-examiner using functional (green) and manual methods (blue) (Pohl et al., 2010). **Schwartz** – SD between-examiner (Schwartz et al., 2004). *Values interpreted from figures.

2.5 Attempts to Improve Marker Placement Consistency

Prior research has shown the lack of consistency in gait kinematic measurements between-days and between-examiners. Further studies attributed the inconsistency primarily to marker placement deviations, with more recent research finding a direct relationship between specific marker placement deviations and the downstream gait kinematic measurements. In response, researchers have investigated the use of various methods to improve marker placement consistency between-days and between-examiners.

2.5.1. Standardized Protocol

As part of the study described in previous sections, Gorton et al. (2009) designed and implemented a standard gait analysis protocol to be used by all 12 clinics participating in the study. One year following the initial round of data collection at all 12 clinics, the single subject returned to each clinic for another gait analysis. Over the course of that year, the examiners at each clinic underwent the same standard gait analysis training (Gorton et al., 2009). The protocol consisted of training videos aimed at standardizing the assessment process, and an in-person training session attended by examiners from all 12 laboratories (Gorton et al., 2009). The same mean joint angles and SD were calculated for the follow-up session. Immediately following implementation of the training protocol, the standard deviation of seven out of nine kinematic measures decreased by an average of 20%, with sagittal plane ankle (30%) and knee (37%) showing the greatest improvement (Gorton et al., 2009). The authors attribute the improvements to knee and ankle kinematics to the training video's focus on knee landmark identification. In addition, the work of Osis et al. (2016) found both the ankle and knee joint to be sensitive to deviations in knee marker placement. While the training protocol improved the consistency of gait kinematic data, considerable discrepancies still existed for some joint angles, and in some cases the standard deviation increased. In addition, a second follow-up analysis, perhaps another year later, would have given insight to whether the examiners retained the same level of consistency or if they would have reverted to the same placement habits they had prior to the standardization attempt.

2.5.2. Functional Approach to Determine Joint Centres

Reverting to bias in marker placement was noted by Leigh, Pohl, and Ferber (2014) when analyzing whether tester experience influenced the consistency of gait kinematic data collection using both a functional and manual method of determining joint centres. Ten healthy subjects made two visits to a gait laboratory, separated by a minimum of two days, to undergo a walking gait analysis. During each visit, two separate gait analyses were carried out; one completed by an experienced examiner with eight years of gait analysis experience, and the other by a novice examiner with four years of clinical experience but no gait analysis experience (Leigh et al., 2014). Before beginning the data collections, the novice examiner underwent a four-part training session conducted by the experienced examiner. The novice examiner observed while the experienced examiner described and demonstrated the correct placement of markers during the first two sessions. The third and fourth sessions involved the novice examiner being responsible for marker placement, under guidance from the experienced examiner during the third session, and fully independent during the fourth session (Leigh et al., 2014). Similar to the methods described in previous sections by Groen et al. (2012), each data collection involved a static trial to determine joint centres using the manual method, and a range of motion trial to determine the functional joint centres of the hip and knee. The authors compared the within-examiner consistency for both the novice and experienced examiner using the CMC and RMSE of the waveforms from day one and two. The authors also explored the between-examiner consistency of the data collected on day two, using the same statistical procedures. Comparisons were made separately for the manual and functional methodology (Leigh et al., 2014).

Within-examiner consistency of the novice examiner was not statistically different from that of the experienced examiner using either the manual or functional methods ($p < 0.05$). CMC

values for within-examiner exceeded 0.90 for all joint angles, using either manual or functional method, and RMSE values were no more than 5° for any joint angle. Between-tester CMC values exceeded 0.87 for all joint angles, using either the manual or functional method, once again suggesting high levels of consistency (Leigh et al., 2014). There was no significant difference in the between-examiner RMSE when comparing the manual and functional methods. The outcomes presented by Leigh et al. (2014) indicate walking gait kinematic data collected by a novice examiner are just as reliable as that collected by an experienced examiner. In addition, the manual and functional methods were shown to be consistent for either a novice or experienced examiner (Leigh et al., 2014). Care must be taken when applying these results to other novice examiners, as the definition of novice may differ from one group to the next. The novice examiner in this case already possessed four years of clinical anatomy experience, therefore it is reasonable to expect different results if the same protocol was applied to a novice with no experience in a clinical or research setting. Another limitation is that the training sessions provided to the novice user occurred just before data collection began. The authors indicate that a six-month follow up analysis of gait kinematic data collected by the novice was trending away from consistency with data collected by the experienced examiner also at a six-month follow-up.

Prior research examining the consistency of a functional approach to determining the joint centre as opposed to the manual method have shown similar results to that of Leigh et al. (2014) (Besier et al., 2003; Pohl et al., 2010). Besier et al. (2003) collected gait kinematic data as ten healthy subjects walked at a self-selected pace along a 10m walkway. Data were collected by two examiners in the morning, and by one examiner in the afternoon, resulting in three gait assessments for each subject. The afternoon examiner was also one of the morning examiners,

allowing for the researchers to explore within- and between-examiner consistency. The authors used the coefficient of multiple determination (CMD), which is the square of CMC, due to the fact that the R^2 value of the CMD indirectly refers to the percent variance explained by the data (Besier et al., 2003). Joint kinematic data was calculated at each of the ankle, knee, and hip, in the sagittal, frontal, and transverse planes. In the between-examiner comparison, CMD ranged from as low as 0.332 for hip transverse plane using the manual method to as high as 0.964 for hip sagittal plane using the functional method. Only the knee frontal plane showed a significant difference in consistency between the manual (CMD = 0.541) and functional method (CMD = 0.742) (Besier et al., 2003). The same relationship was observed for the within-examiner comparison, as only the knee frontal plane kinematics showed a significant difference in consistency between the manual (CMD = 0.589) and the functional method (0.714). Pohl et al. (2010) also determined there was no significant difference in consistency of gait kinematics between the manual and functional methods. Examining the treadmill running gait of ten healthy runners, the researchers collected gait kinematic data on three separate days. On day one and two marker placement and analysis were conducted by the first of two examiners. On day three the second examiner was responsible for the assessment (Pohl et al., 2010). Each assessment involved a static trial and a range of motion trial. Using similar methods to Besier et al. (2003), waveform data were calculated for each of the ankle, knee, and hip, in the sagittal, frontal, and transverse planes. The authors used CMC, RMSE, and range of motion (ROM) to represent the between- and within-examiner consistency of gait kinematic data using the manual and functional method (Pohl et al., 2010). With the same hypothesis as Besier et al. (2003), the data indicated no difference in gait kinematic consistency between the manual and functional method for running (Pohl et al., 2010).

Research for walking and running gait shows no substantial improvement in consistency when using a functional method to calculate the joint centres as opposed to the manual method (Besier et al., 2003; Leigh et al., 2014; Pohl et al., 2010). Besier et al. (2003) acknowledges that all examiners involved in marker placement were experienced in locating anatomical landmarks for gait analysis, and presents this as a possible reason for not finding a significant difference. However, Leigh et al. (2014) incorporated both an experienced and novice examiner into the data collection and continued to see no difference in the resulting consistency of gait kinematics. Although, as mentioned earlier, the consistency of the data between the expert and novice may be a result of the in-depth training received by the novice prior to data collection. In summary, both the manual and functional methods require anatomical landmark identification during the collection process, and it is suggested that steps to improve landmark identification and marker placement are taken, irrespective of the methodology being used.

2.5.3. Marker Placement Devices

In addition to testing different methodologies, other researchers have explored the use of specific devices to improve marker placement consistency (Kalkum et al., 2016; Noehren et al., 2010; Telfer et al., 2010). The marker placement devices incorporate laser pointers fixed to adjustable arms (Kalkum et al., 2016; Noehren et al., 2010), or markers stacked longitudinally along a bent plastic wire (Telfer et al., 2010) to consistently replicate the marker positions of a previously recorded trial. The device implemented by Noehren et al. (2010) requires the subject to stand partially enclosed by the apparatus, with markers already placed at the desired anatomical landmarks, meanwhile the adjustable arms are positioned so that each laser points directly to the centre of the corresponding marker (Figure 2-4). The position (mm) of each laser is recorded. Then, prior to a follow-up session, the laser pointers can be positioned to guide the

placement of markers (Noehren et al., 2010). The device designed by Kalkum et al. (2016) uses the same principle as Noehren et al. (2010), however the authors focused only on the foot and ankle, and therefore the subject can be seated during the placement of markers and adjustment of the laser pointers.

Figure 2-4: Image of marker placement device used by Noehren et al. 2010. Image on the left shows adjustable arms, upper (A) and lower (B), used to position laser pointers, as well as the additional padding (C) to support the back of the subject. The image on the right shows the device set-up with subject. *With permission* (Noehren et al., 2010).

To determine the effectiveness of the device, ten healthy subjects made three visits to the lab over seven days (Noehren et al., 2010). Each visit consisted of a static trial and running trial

on an instrumented treadmill. A single, experienced examiner was responsible for all marker placements. During the first visit the examiner placed markers on the desired anatomical landmarks, a static trial was collected, the position of the subject on the treadmill was standardized, and finally a running trial was captured. Upon the second visit, the same marker set-up was carried out, but before collecting a static trial the subject stood in the marker placement device and the position of each marker was recorded by aligning each laser pointer with centre of its corresponding marker. The second visit concluded with another running trial. On the third visit the marker placement was guided by aligning the laser pointers using the position data recorded during the previous visit. Finally, a third running trial was collected. Peak joint kinematics were calculated at the ankle, knee, and hip, in the sagittal, frontal and transverse plane. The kinematic consistency of the first and second trials represented the manual placement method, while the consistency of the second and third trials represented that of the marker placement device (Noehren et al., 2010). The authors used ICC (3, k) to represent the consistency of the discrete peak angles, and the standard error of measurement (SEM).

With a focus on the joint kinematics of a multi-segment foot and ankle, Kalkum et al. (2016) tested a marker placement device on 38 subjects undergoing three taping conditions and one barefoot condition. All four conditions were followed by a single static trial, and all data was collected on the same day for a given subject. Following the initial marker placement, the subject sat with the investigated foot in the device, and the opposite foot outside the device at level height (Kalkum et al., 2016). Similar to Noehren et al. (2010), laser pointers were positioned so that the laser was aimed at the centre of the respective marker. The position of the laser could be not translated along the arms of the device, but a miniature tripod allowed the laser

to pivot in place in order to locate the marker (Kalkum et al., 2016). Static trial measurements of the multi-segment foot were calculated for each of the four trials and compared using ICC.

Telfer et al. (2010) also focused solely on foot and ankle kinematics, however their device did not rely on the positioning of lasers. Following landmark identification with permanent ink, the authors used a bent plastic wire, with markers stacked along the length of the wire. A hole, with radius slightly larger than that of the wire, was drilled into each marker to allow them to slide up and down the length of the device (Telfer et al., 2010). The tip of the wire was placed on the target mark, and used to guide the marker down to that location. The joint kinematics of a multi-segment foot model during five, over-ground walking trials were calculated using two static trials pertaining to an expert examiner marker placement and two trials of a novice examiner using the device to guide marker placement (Telfer et al., 2010). The authors calculated ICC to represent consistency of discrete variables, and CMC to analyze the waveform data.

The use of each marker placement device described above showed considerable improvement in gait kinematic consistency. With the use of a marker placement device Noehren et al. (2010) increased the ICC value for eight out of nine joint angles, while the ninth, knee sagittal plane, remained unchanged. All ICC values were greater than 0.82, and seven out of nine exceeded 0.90 (Noehren et al., 2010). The ICC value for discrete static measurements of a multi-segment foot model ranged from 0.91 – 0.97 (Kalkum et al., 2016). Also examining a multi-segment foot, Telfer et al. (2010) found, in general the between-session consistency of the waveform data improved with the use of the novel placement device, but while the ICC values indicated good consistency (ranging from 0.803 – 0.998), only five out of eight variables showed improvement with the use of the device.

The initial findings regarding improved gait kinematic consistency with the use of marker placement devices are encouraging, however the findings must be interpreted with caution. In all three examples, the device is dependent on initial landmark identification by an expert. Without a consistent source of initial landmark identification these devices are no longer effective. As limitation addressed by the authors, the device implemented by Kalkum et al. (2016) is restricted to within-day use, and not suitable for longitudinal studies. Last of all, the marker placement devices described require additional time for set-up and calibration, requiring the subject stand motionless for up to ten minutes (Noehren et al., 2010). Time is an important resource to a clinician that hopes to consult multiple patients, and therefore any tool that is designed to improve marker placement consistency should be able to do so in a short amount of time.

2.6 Multi-Centre Collaboration

In the development of an online gait repository system, Tirosh, Baker, and McGinley (2010) highlight the need for shareable gait data within the clinical gait analysis community. The authors suggest access to shareable gait data would improve decision making across multiple clinics by facilitating collaboration and consultation between groups (Tirosh et al., 2010). Not having a large enough sample size is commonly found as a limitation among gait research to date (Ferber et al., 2002; Sinclair et al., 2012; Szczerbik & Kalinowska, 2011; Winter, 1984). A growing database of gait data would also provide access to large sample sizes of data for analysis, thereby increasing the power and generalizability of results (Myer et al., 2014). Despite the clear benefit that a multi-centre gait database can provide, research continues to show that inconsistencies in gait kinematic data are abundant. Without a tool to improve gait kinematic consistency the full potential of multi-centre collaboration will not be reached.

2.7 Real-Time Marker Placement Feedback Tool

Recently, Osis et al. (2014) developed a feedback tool that provides real-time, quantitative feedback regarding marker placement error. The feedback tool references a gold-standard cohort of 340 subjects, all of which were assessed by the same examiner with 15 years of experience in a clinical gait setting (Osis et al., 2014). When any subsequent examiner collects a static trial using the same marker set as the reference database, the marker locations for that trial are imported to the feedback tool. Next, the tool applies a series of translations and rotations to the marker position data which allows the current static trial to be compared to a morphometric norm (Osis et al., 2014). The tool then compares the normalized marker position data from the current trial to the entire group of 340 expert datasets, and extracts a subgroup of the 10 closest expert datasets pertaining to each of 50 marker coordinates (25 markers x AP and vertical). Any expert dataset that exists in four or more of the 50 subgroups is included in the anatomically similar reference cohort, consisting of 10-20 datasets (Osis et al., 2014). The reference cohort provides the necessary information to determine the inter-quartile range ratio (IQRR) for each marker coordinate, defined as the ratio of the difference between the marker coordinate for the current trial and the median marker coordinate of the reference cohort to the inter-quartile range of the reference cohort (Equation 1) (Osis et al., 2014).

$$IQRR = \frac{y_{\text{Novice}} - \tilde{y}_{\text{Expert}}}{IQR_{\text{Expert}}} \quad (1)$$

Where:

y_{Novice} = Marker coordinate of novice data

$\tilde{y}_{\text{Expert}}$ = Median marker coordinate of expert subgroup

IQR_{Expert} = Inter-quartile range of expert subgroup

The real-time feedback tool provides the direction and relative magnitude of the deviation of each marker placement, in a unit-less IQRR space, allowing the tester to adjust marker placements on the subject prior to collecting the next static trial and subsequent dynamic trials. The authors tested the efficacy of the training tool by tracking the gait assessments made by a novice clinician, with no research or clinical assessment background, but six years of experience with clinical anatomy. The novice received feedback, regarding marker placement, from two experienced clinicians throughout each assessment, and completed 55 assessments over the course of the year (Osis et al., 2014). For each novice clinician's assessment, the marker placement deviations relative to the expert were recorded. The authors found that while the novice clinician's marker placement deviation decreased over the course of the year, and the software feedback tool was capable of detecting systematic differences in the marker placement that the two experienced clinicians did not notice or correct for.

2.7.1. Preliminary Research

Osis et al. (2016) demonstrated that novice examiners, with no biomechanics or gait analysis experience, could improve the median deviation in discrete kinematic variables by up to

80% relative to those determined by an expert marker placement. Peak joint angles were calculated at the ankle, knee, and hip, in the sagittal, frontal, and transverse plane. On average, the median deviation to the expert trended towards zero in seven out of nine variables (Osis et al., 2016). The authors note that the trend towards zero was not consistent across all participants as some were found to over-correct their placements once being given feedback, and these differences pre- and post-feedback were significant only for peak knee flexion and hip extension ($p < 0.05$). Although further testing of the real-time feedback tool is needed, there is potential to greatly reduce marker placement error, and act as an educational tool for novice users. However, further research is necessary to understand the role of real-time marker placement feedback, and its ability to improve marker placement consistency among novice examiners over multiple data collections.

2.8 Purpose

Despite being recognized as the gold standard for determining gait kinematics in walking and running, 3DGA is limited by marker placement inconsistency. The between-session, between-tester, and between-laboratory error introduced by deviations in marker placement has the potential to cause misinterpretation of the resulting gait kinematic data. Alternative methodologies and marker placement devices have either shown inconsistent results or clinically impractical protocols. Improved technology has led to the development of a real-time feedback tool for increasing marker placement consistency. Preliminary research shows promising results in terms of improving the consistency of gait kinematic data collected by a group of novice users, however further research is necessary to determine the efficacy of the real-time feedback tool among a larger sample of users, and across multiple testing sessions. Therefore, the purpose of the current study was to increase marker placement consistency and improve upon previous

attempts at standard protocols and placement devices by providing real-time feedback, not requiring timely set-up and operation, and not relying on initial marker placement by an expert examiner for each data collection. Similar to previous literature we hypothesized the gait kinematic data associated with post-feedback trials would show increased consistency, in the form of decreased 95% CI range. We also hypothesized the ankle transverse, knee frontal, and hip frontal plane joint kinematics will display the largest reductions in 95% CI range of mean joint angle. This is in response to the results of Osis et al. (2016) showing that ankle transverse, knee frontal, and hip frontal plane kinematics are most sensitive to simulated marker placement deviations.

CHAPTER THREE: METHODS

3.1. Participants

All 3DGA trials were conducted on a single runner (male, 24 years, 188 cm, 75 kg). The uninjured, recreational runner was free of any lower limb deformities or surgical changes that might have affected his gait.

Twelve kinesiology students from a university campus assumed the role of examiner. The novice examiners had completed courses in human anatomy, and introductory biomechanics, however, none had any experience locating anatomical landmarks for the purpose of 3DGA. All individuals provided written informed consent (Appendix A) prior to participation in the study, in accordance with the institution's research ethics board (REB16-0149).

3.2. Experimental Protocol

All 12 novice examiners visited the lab individually, and were provided a schematic of the target anatomical landmarks (Figure 3-1) accompanied by a brief written description of landmark location (Appendix D) and minimal verbal instruction. Examiners placed retroreflective markers (9.5 mm diameter, Mocap Solutions, Huntington Beach, CA, USA) on the runner at the following bilateral landmarks: first and fifth metatarsal heads; medial and lateral malleoli; medial and lateral knee joint lines; tibial tuberosity; fibular head; greater trochanter; ASIS; iliac crest. An anatomical model of the lower extremities was created according to previously published methods (Osis et al., 2016, 2014). Rigid marker clusters, consisting of 3-4 markers each, were fastened over the sacrum, and bilaterally on the thigh and shank. Three technical markers were taped to each shoe (Nike Air Pegasus, Nike Inc., Beaverton, OR, USA) defining the foot segment. The marker clusters were used to define the SCS at the thigh, shank,

and foot (Mills, Hettinga, Pohl, & Ferber, 2013). To reduce the impact of clothing on marker placement, the runner wore a tight-fitting shirt and shorts.

Figure 3-1: Schematic showing anterior and posterior marker locations. Grey markers, placed by the examiners, are used to define virtual joint centres (Cole et al. 1993).

Technical markers were fixed to a rigid shell and used during both static and running trials. This diagram was presented to all examiners, along with a brief description of each anatomical landmark. Adapted from Pohl et al., 2010.

Following marker set-up, the runner stood on a treadmill (Bertec, Columbus OH, USA) to collect the first static trial. The runner's position was standardized using a graphic template.

Seven high speed digital cameras recording at 200Hz (MX-3, Vicon, Oxford, UK) collected 3D marker coordinate data. Cameras were calibrated by the same researcher prior to every session using an L-frame wand. Static trial marker coordinates were reconstructed and labelled according to each landmark using Vicon Nexus software (Vicon, Oxford, UK). Once thoroughly labelled, the marker data were imported to the real-time feedback software tool which displayed a standardized 3D plot for the examiner (Osis et al., 2014). The plot displayed static trial marker coordinates, along with expected marker coordinates according to static trial data from a previous cohort of subjects collected by a single experienced examiner (Osis et al., 2016, 2014) (Figure 3-2). The novice examiner was instructed to use his/her judgement to adjust the markers, according to the direction and magnitude of deviation observed on the 3D plot. No scale or measurement information were displayed. Following marker adjustment, a second static trial was collected. The anatomical markers were then removed, and only the rigid marker clusters remained in order to collect a dynamic running trial at a controlled speed of 2.7 m/s. Following a 30 second acclimatization period, 60 seconds of kinematic data were collected. The running trial was processed using both static trial conditions collected prior to and following use of the marker check feedback program.

Figure 3-2: Screenshot of the placement feedback presented to the examiners. Expected marker placements (green circles), along with marker placements from the current trial (blue and red circles) were scaled to fit the 3D model of the lower-limb. A connecting line between anatomical marker location and expected marker location indicates direction of deviation. No scale or measurement information was provided. Blue circles indicate marker placement deviation within the IQRR threshold (0.8), while red circles indicate marker placement deviation outside of the IQRR threshold. *With permission* (Osis et al., 2016).

All 12 examiners visited the lab on two occasions, separated by one week, resulting in 24 total data collections over the course of eight weeks. Set-up and protocol from day one was repeated for day two, resulting in four unique static trial conditions for each examiner.

3.2.1 Real-time Feedback

The real-time feedback tool, developed by Osis et al. (2014), provides the examiner with a quantitative representation of marker placement deviation. As outlined by Osis et al. (2014), novel software references a cohort of 340 previously collected static trials, of which all marker placements and assessments were performed by a single expert examiner with over 14 years of experience in clinical anatomy. A specific series of translations and rotations are made to the entire cohort of marker coordinate data creating a morphometric norm and eliminating any subtle differences in the subject's stance during their data collection (Osis et al., 2014). Following the collection and proper labelling of a subsequent static trial, the same set of translations and rotations are made to compare the new trial to the morphometric norm. The tool extracts a subgroups of the 10 closest expert datasets pertaining to each of 50 marker coordinate (25 markers x AP and vertical coordinate), and any expert dataset that is selected in four or more of the 50 subgroups is included in the final reference cohort of 10-20 datasets (Osis et al., 2014).

Marker coordinate data from the reference cohort of 10-20 expert datasets is analyzed and an inter-quartile range (IQR) is determined for each marker location in the AP and vertical direction. The IQR allows for the calculation of the IQRR which is defined as the ratio of the difference between the current trial marker coordinate and the median marker coordinate of the reference cohort to the IQR (Osis et al., 2014). Upon loading the real-time feedback tool, the examiner is provided with a 3D plot of the right and left lower extremity, in unit-less IQRR

space, which includes the expected marker placement location and the actual placement for each marker represented by two different coloured circles. A blue circle indicates a marker that is within an acceptable IQRR threshold, and a red circle indicates a marker outside of the acceptable threshold. The cut-off range is defined *a priori*. The direction and magnitude of the deviation is represented by a solid black line joining the two circles. As described above, the examiner references the 3D plot to guide any necessary adjustment of marker placements.

3.3. Data Processing

Marker data from the running trials were low-pass filtered using a 2nd order recursive Butterworth filter with a 10 Hz cutoff. Joint kinematics were calculated bilaterally at the ankle, knee, and hip joint in the frontal, transverse, and sagittal plane using a singular value decomposition method (Soderkvist & Wedin, 1993) and JCS (Cole et al., 1993). To determine the JCS the following joint centre locations were defined using the anatomical markers. In short, the ankle joint centres were located at the midpoint between the medial and lateral malleoli markers. Knee joint centres were located at the midpoint between the medial and lateral knee joint line markers. The hip joint centres were defined using the right and left greater trochanter markers and locating the centres at 25% of the distance between them (Osis et al., 2014). Next, the JCS for each segment was constructed so that the long axis was aligned with the vector connecting two adjacent joint centres. The flexion axis was determined to be orthogonal to the long axis and in line with the vector connecting the medial and lateral joint markers. Last of all, the anterior axis was calculated to be the cross product of the flexion and long axes. The orientation and position of the rigid marker clusters described in Section 2.2 were tracked in relation to the defined JCS. Angular kinematic data from the running trial were normalized to a

single stride with 100 time points, and toe-off occurring at 40% of the stride. All data were post-processed using custom MATLAB 9.1 software (Mathworks Inc., Natick, MA, USA).

3.4. Data Analysis

Waveform data were grouped according to nine joint kinematic parameters (ankle, knee, hip x frontal, transverse, sagittal). Joint angular data pertaining to each examiner were separated by static trial condition: before feedback on day one (PRE1), after feedback on day one (POST1), before feedback on day two (PRE2), and after feedback on day two (POST2). Since the same runner was used for all data collections, left and right limb data were analyzed together, resulting in 24 waveforms (12 examiners x two limbs) pertaining to each of the four static trial conditions.

Mean joint angle was reported to be a sensitive indicator of kinematic similarity between conditions that can provide a single representative value of the entire stride (Gorton et al., 2009). To test for differences in mean joint angle, the Shapiro-Wilks test for normality was conducted due to its suitability for small sample sizes. Friedman's test determined if there was a significant effect of static trial condition on mean joint angle. If a significant difference between conditions was present, a post-hoc Wilcoxon-Signed Rank test was performed with Bonferroni correction for multiple comparisons ($\alpha = 0.05$).

While the mean joint angle was not expected to differ with feedback, it was expected that the between-examiner consistency of mean joint angle would improve as a result of increased marker placement consistency. The 95% CI of resulting mean joint angles represented the between examiner consistency and served as the primary dependent variable. Mean joint angles

were averaged across all examiners and both limbs, then compared between static trial conditions.

Previous literature has shown a variety of methods to calculate the consistency of multiple waveforms, including the CMC (Equation 2), RMSE (Equation 3), and ROM (Equation 4) (Kadaba et al., 1989; Leigh et al., 2014; Noehren et al., 2010; Pohl et al., 2010).

$$CMC = \sqrt{1 - \frac{\sum_{i=1}^M \sum_{t=1}^T (Y_{it} - \bar{Y}_t)^2 / T(M-1)}{\sum_{i=1}^M \sum_{t=1}^T (Y_{it} - \bar{Y})^2 / (MT-1)}}$$

(2)

Adapted from Kadaba et al. (1989), where:

M = Number of trials

T = Number of time points per waveform

Y_{it} = Joint angle corresponding to i th trial and t th time point

$\bar{Y}_t$ = Mean joint angle at t th time point for all trials M

$\bar{Y}$ = Grand mean joint angle of all time points T for all trials M

$$RMSE = \sqrt{\frac{\sum_{i=1}^T (x_i - y_i)^2}{n}}$$

(3)

Where:

x and y are two waveforms being compared

T = Number of time points per waveform

x_i = Joint angle at i th time point for x

y_i = Joint angle at i th time point for y

$$ROM = |\max(x_{i=1 \rightarrow T}) - \min(x_{i=1 \rightarrow T})| \quad (4)$$

Where:

x = Waveform under consideration

T = Number of time points per waveform

For two reasons the 95% CI of the mean joint angle was used to represent gait kinematic consistency. The first being that methods such as the CMC and ROM consider aspects of the shape of two waveforms of interest, with the CMC considering the entire waveform, and the ROM focusing on the maximum and minimum values. In the present study, the comparisons made were between waveforms that pertained to the same dynamic trial, but with different static trials. Therefore, we do not expect any substantial change in shape, but rather a shift in the waveform along the y-axis, thereby resulting in relatively high levels of consistency for CMC and ROM regardless of marker placement deviation (Figure 3-3). As Figure 3-3 shows, CMC does not reflect the improved marker placement consistency of plot (B) as compared to plot (A). For the same reason the RMSE, which calculates the mean residuals between two waveforms across all time points, was determined to be redundant with the 95% CI if the primary difference between two waveforms is a vertical shift. The second reason for using the 95% CI is the ease of which the results can be understood in a clinical setting. The CMC outputs a coefficient from 0 to 1 which can be difficult to interpret despite its use in literature. The 95% CI reports a range of joint angles that are easy for both a clinician and researcher to interpret in terms of each joint angle, making it an ideal measure of gait kinematic consistency among a group of novices.

A secondary measure of consistency, the absolute range of mean joint angles, provided insight into the maximum and minimum values obtained by the examiners for each static trial condition. All statistical analysis was completed using SPSS 24.0 (SPSS Inc., Chicago, USA).

(A) CMC = Error, RMSE = 9.79° , Diff. ROM = 0.74° , Diff. Mean = 9.74°

(B) CMC = 0.988, RMSE = 0.71° , Diff. ROM = 1.92° , Diff. Mean = 0.11°

Figure 3-3: Representative waveform data showing the statistical breakdown of the CMC when a large offset exists between waveforms resulting in an undefined correlation (A), and the inconsistency of reporting difference in ROM (A) and (B). The RMSE and difference in mean joint angle are more representative of differences between waveforms.

CHAPTER FOUR: RESULTS

4.1 Mean Joint Angle

Friedman's test revealed no significant effect of static trial condition on mean joint angle for eight out of nine joint angles. A significant effect was observed in the hip sagittal plane, $\chi^2(3, N = 24) = 11.95, p = 0.008$. Post-hoc tests indicated no significant difference in PRE1 vs PRE2 ($Z = -0.057, p = 0.954$), or POST1 vs POST2 conditions ($Z = -0.886, p = 0.376$). However, significant differences were observed between PRE1 and POST1 conditions ($Z = -3.00, p = 0.003$) and PRE2 vs POST2 conditions ($Z = -2.80, p = 0.005$).

4.2 Day 1 Consistency

Mean joint angle and 95% CI for the PRE1 and POST1 conditions are presented in Table 4-1. In terms of between-examiner consistency, use of the real-time feedback tool reduced the 95% CI range for eight out of nine joint angles by an average of 27.45%. The ankle transverse, hip frontal, and hip sagittal planes showed the greatest reduction. The 95% CI at the ankle transverse plane, in the PRE1 condition ($-4.03^\circ, 0.23^\circ$) was reduced by 22.77% in the POST1 condition ($-5.61^\circ, -2.32^\circ$). The hip frontal plane reduced by 47.01% from PRE1 ($-2.96^\circ, -0.45^\circ$) to POST1 ($-3.28^\circ, -1.95^\circ$). The hip sagittal showed the greatest reduction, 55.94% from PRE1 ($-19.14^\circ, -13.58^\circ$) to POST1 ($-14.07^\circ, -11.62^\circ$). Figure 4-1 shows a graphical representation of the reduced 95% CI for the joint angles listed above. The ankle frontal plane showed only slight reduction (4.92%), and was not considered among the eight joint angles that showed improvement with feedback.

Table 4-1: Mean joint angle and 95% confidence interval (CI) for each joint kinematic measure corresponding to all four static trial conditions (n = 24). Bonferroni correction is applied for multiple comparisons.

		PRE1	POST1	PRE2	POST2
		$\bar{X}$			
		95% CI [Lower, Upper]			
Ankle	Frontal	-7.13 [-7.74, -6.52]	-7.05 [-7.63, -6.47]	-6.57 [-7.06, -6.08]	-6.74 [-7.23, -6.25]
	Transverse	-1.90 [-4.03, 0.23]	-3.97 [-5.61, -2.32]	-4.63 [-6.64, -2.62]	-6.03 [-7.61, -4.45]
	Sagittal	1.11 [-0.25, 2.48]	1.42 [0.24, 2.60]	2.65 [1.79, 3.51]	2.19 [1.12, 3.26]
Knee	Frontal	9.10 [7.41, 10.79]	9.26 [7.86, 10.65]	9.20 [7.93, 10.47]	10.08 [9.03, 11.12]
	Transverse	15.14 [11.66, 18.63]	12.73 [9.74, 15.71]	15.19 [12.37, 18.01]	14.37 [11.04, 17.70]
	Sagittal	42.88 [40.94, 44.82]	42.39 [40.82, 43.97]	40.76 [38.69, 42.82]	41.18 [39.41, 42.94]
Hip	Frontal	-1.71 [-2.96, -0.45]	-2.61 [-3.28, -1.95]	-2.08 [-3.13, -1.03]	-2.62 [-3.36, -1.88]
	Transverse	-8.17 [-11.30, -5.04]	-4.91 [-7.11, -2.71]	-6.62 [-9.13, -4.11]	-5.10 [-7.82, -2.38]
	Sagittal *^	-16.36 [-19.14, -13.58]	-12.85 [-14.07, -11.62]	-15.55 [-17.49, -13.61]	-13.14 [-14.30, -11.99]

*** Difference in mean joint angle between PRE1 and POST1 ($\alpha = 0.05$)**

^ Difference in mean joint angle between PRE2 and POST2 ($\alpha = 0.05$)

4.3 Day 2 Consistency

Mean joint angle and 95% CI for PRE2 and POST2 conditions are presented in Table 4-1.

1. In terms of between-examiner consistency, use of the real-time feedback tool reduced the range of the 95% CI for five out of nine joint angles by an average of 24.73% (Table 4-1) and all five parameters demonstrated a reduction in the 95% CI on day one as well. Consistent with day one, the greatest reductions were seen in the ankle transverse, hip frontal, and hip sagittal planes. Ankle transverse reduced by 21.39% from PRE2 (-6.64° , -2.62°), to POST2 (-7.61° , -4.45°). Hip frontal plane reduced by 29.52%, from PRE2 (-3.13° , -1.03°) to POST2 (-3.36° , -1.88°). Hip sagittal plane showed the greatest reduction, 40.46%, from PRE2 (-17.49° , -13.61°) to POST2 (-14.30° , -11.99°). Figure 4-1 shows a graphical representation of the reduced 95% CI for the above parameters. Use of the feedback tool increased the 95% CI for ankle sagittal, knee transverse, and hip transverse by an average of 16.96%, while the 95% CI range for the ankle frontal plane did not change (Table 4-1).

Figure 4-1: Visual representation of 95% confidence interval (CI) of mean joint angles for select joint angles; ankle transverse, knee frontal, hip sagittal, and hip frontal planes. The x-axis represents the four static trial conditions. The 95%CI for each bar is centered on the group average mean joint angle (n = 24). *Significant differences in mean joint angle ($\alpha = 0.05$), with Bonferroni correction for multiple comparisons.

4.4 Between-Day Consistency

Eight out of nine joint angles showed a reduced range of 95% CI in the POST2 condition, relative to PRE1, by an average of 28.36% (Table 4-1). Knee transverse plane displayed only a slight reduction (4.45%).

Waveform plots of mean joint angle range for the PRE1, PRE2, and POST2 conditions are overlaid in Figure 4-2, emphasizing the reduced absolute range of the mean joint angle data

throughout an entire stride. The upper and lower bands represent the maximum and minimum joint angle, respectively, at each percent of stride for all examiners.

Figure 4-2: Waveform plots of select joint angles: ankle transverse, knee frontal, hip sagittal, and hip frontal planes. At each of 100 time points, corresponding to percent of stride, the maximum and minimum mean joint angle ($n = 24$) was plotted as the upper and lower bands of the waveform. Data span the entire stride, showing variations in consistency of a group of novice examiners at different points during the stride. For clarity, the POST1 condition is omitted due to its resemblance to the PRE2 condition.

CHAPTER FIVE: DISCUSSION AND CONCLUSION

5.1. Discussion

The aim of the study was to determine whether a real-time feedback tool improves marker placement consistency for a group of novice examiners. In support of the hypothesis, use of the feedback tool suggested a trend towards improvement in marker placement consistency for the group of novice examiners by decreasing the range of the 95% CI for mean joint angles. Previous research has outlined the effect of marker placement deviation on downstream gait kinematic variables, and has shown that improvements in the consistency of these variables can be achieved by reducing marker placement deviation (Della Croce et al., 2005; Gorton et al., 2009; Groen et al., 2012; Noehren et al., 2010). The results confirm the relationship between marker placement and gait kinematic variables, the positive effect of improved marker placement consistency, and that improvement can also be shown during a one-week follow-up session

On day one, improved gait kinematic consistency was observed for eight out of nine joint angles and was also evident on day two, as five out of nine joint angles showed a reduced 95% CI after examiners were provided with visual feedback. Between days, eight out of nine joint angles exhibited reduced 95% CI in the POST2 condition relative to PRE1. When interpreting the role of feedback on day two, it is also important to consider that gait kinematic consistency in the PRE2 condition was improved relative to the PRE1 condition for eight out of nine joint angles, and, more importantly, for all four joint angles that did not show improvement from PRE2 to POST2. Therefore, the inability of the real-time feedback tool to improve consistency on day two to the same extent as day one is more likely a product of this potential learning effect. Only the hip sagittal plane demonstrated a significant difference in mean joint angle between

conditions. However, we did not expect the mean joint angle to differ substantially between conditions as this value reflects the within-subject consistency of the runner.

The results agree with those of the marker placement simulation by Osis, Hettinga, Macdonald, & Ferber (2016), as joint kinematics in the ankle transverse, knee frontal, and hip frontal plane were among the variables that were most positively influenced by use of the feedback tool. Osis et al. (2016) showed that transverse and frontal plane kinematics are most notably affected by simulated marker placement deviation. One of the key findings from Osis et al. (2016) was the large influence of the ankle marker on both ankle transverse and knee transverse plane motion, echoing prior research that suggests frontal and transverse planes are most sensitive to marker placement error (McGinley et al., 2009; Schwartz et al., 2004). Comparable results were noted when considering the absolute range of mean joint angles. As seen in Figure 4-2, use of the feedback tool on day two resulted in a 7.27° reduction in the range of mean angles in the ankle transverse plane, a similar magnitude to the 7.50° of kinematic change observed in the ankle transverse plane as a result of misplacing the malleoli marker by 10mm in the anterior-posterior direction (Osis et al., 2016). These findings are substantial considering McGinley et al. (2009) indicate joint angle errors between 2° and 5° should be interpreted with caution, and errors exceeding 5° are enough to misguide clinical interpretation.

In agreement with the results of Gorton et al. (2009), the use of the feedback tool reduced the range of mean joint angles in the hip frontal plane, as well as knee and hip sagittal planes, in a similar manner to the implementation of the standard placement protocol. However, in contrast, the real-time feedback tool did not improve consistency in the ankle sagittal plane. The improved consistency of most but not all joint angles highlights the feedback tool's proficiency in improving placement consistency at the hip and knee joint, however, further refinement might

be necessary for other joint locations such as the ankle. The feedback tool did not improve consistency across as many joint angles as the marker placement device introduced by Noehren et al. (2010), which was more effective than the feedback tool at improving consistency in the transverse plane. However, it is difficult to make a direct comparison between studies, as the primary measures of consistency between the current study and that of Noehren et al. (2010) are different. While measures of performance regarding gait kinematic consistency are comparable to those of previous devices and protocols, the feedback tool proves superior in methodology to other placement devices and standard protocols by allowing for real-time feedback, and continuous monitoring of the examiner's placement consistency over multiple days.

5.2. Clinical and Research Applications

In clinical and research practice, 3DGA often involves baseline testing followed by at least one follow-up session. During the time between these sessions a specific training protocol or intervention is undertaken. The period of time from baseline to follow-up is dependent on the intervention or the research question being posed, however examples from the literature show ranges from one week to over 15 months (Beaulieu et al., 2010; Gaudreault et al., 2011; Sartor et al., 2012; Steinwender et al., 2000; Watari, Kobsar, Phinyomark, Osis, & Ferber, 2016). As the time interval increases, so does the likelihood of introducing error due to marker placement deviation. The chance of marker placement error becomes especially prevalent if multiple examiners are involved in subject set-up (between-examiner consistency), but even so in the case of one examiner being responsible for all marker placements (within-examiner consistency). Considering previous research suggests up to 75% of the kinematic variability of between-day comparisons is due to marker placement deviations, for a group of experienced examiners, a tool

that improves placement consistency is critical for studies that plan to investigate longitudinal changes in gait (Gorton et al., 2009).

As the number of laboratories and clinics using 3DGA increases, the potential for multi-centre collaboration continues to grow. The feedback tool described in the current study would enable multiple institutions to establish consistent benchmarks, share data, and encourage consultation between partner clinics (Brophy et al., 2012; Myer et al., 2014; Tirosh et al., 2010). Large databases of 3DGA data would provide the resources to overcome the common limitation of small sample size reported by much of the current literature surrounding gait analysis, potentially allowing for greater generalizability of results (Laroche et al., 2011; Leigh et al., 2014; McGinley et al., 2009; Noehren et al., 2010). An inherent problem with multi-center investigations is the introduction of between-examiner error, and the inconsistency in marker placement despite the introduction of standard procedures (Gorton et al., 2009). The between-examiner results of the current study indicate a potential solution to this inconsistency, showing that for a group of novice examiners the range in mean joint angle is reduced after using the feedback tool. Moreover, the positive effect of the tool is still observed during a follow-up session, one week later.

Frontal plane kinematics of the knee and hip have been identified in research surrounding the aetiology of knee osteoarthritis (OA) and the difference in prevalence between males and females (Phinyomark, Osis, Hettinga, Kobsar, & Ferber, 2016). Again working with a sample of individuals with knee OA, research has shown difference in hip frontal plane kinematics between those that were classified as high-responders to treatment as compared to those that were grouped into the low- or non-responder category (Kobsar, Osis, Hettinga, & Ferber, 2015). The potential to predict with high accuracy whether a patient will respond well to a specific treatment

has meaningful implications for clinical practice by saving time and resources. However, the prediction may be improved with more gait kinematic consistency at the joint angle of interest. Using a similar methodology to distinguish responders and non-responders to treatment for patellofemoral pain syndrome, indicates greater knee abduction in those individuals that responded well to treatment (Watari et al., 2016). Improved reliability of joint kinematics in the transverse and frontal plane is critical as literature continues to indicate the important role that these joint motions might play in both research and clinical settings.

5.3. Limitations

The study outcomes must be interpreted in the context of specific limitations. First, the marker placement feedback provided by the system is fully dependent upon the static trials that compose the reference database. The current iteration of the real-time feedback tool is comprised of healthy adults, with no known pathologies that would affect lower extremity morphology. While comprising the database with healthy adults is ideal in the case of the current study involving a single healthy runner free of lower limb pathology, care must be taken when applying the placement feedback to individuals with surgical changes, or developmental disorders affecting posture or anatomical alignment. However, one of the strengths of the feedback tool is that the reference database can be easily adjusted and expanded to include more individuals that possess similar morphological characteristics to the target individual (Ferber, Osis, Hicks, & Delp, 2016; Osis et al., 2016). In a similar fashion, the study's outcomes must be interpreted within the context of the JCS used, which may vary between research groups. Previous research suggests the relationship between marker misplacement and gait kinematic consistency is dependent upon the methods used to determine the JCS (Della Croce et al., 2005; Ferber et al., 2002; Gorton et al., 2009).

The possibility of within-subject gait variability must be acknowledged considering that data were collected over an eight-week period, despite the single runner being healthy and free of any musculoskeletal injury. While statistical tests showed no difference in mean joint angle between days (Table 4-1), it is possible that slight variations in the runner's gait kinematics could have influenced the calculation of the 95% CI. Future investigations are encouraged to limit the period of time over which data are collected, similar to the protocol used in the pilot study by Osis et al. (2016). In an ideal case, the 12 examiners would have visited the lab separately over the course of the same day allowing for only one run trial to be collected after all static trials were complete. The same process would then be repeated during the follow-up session. While collecting data from all examiners during a single day may have improved the data quality, it is worth noting that within-subject error is considered to contribute minimally to the overall inconsistency of gait kinematic data (Gorton et al., 2009; Schwartz et al., 2004). Depending on the research question, the logistical concerns of coordinating that many subjects to visit the laboratory on one day may not be worth the minimal return in terms of increased data consistency.

The generalizability of results may be improved with a more diverse sample of novice examiners, as the 12 examiners were a sample of convenience from the same institution. A potential next step to test the feedback tool would be to incorporate novice examiners from multiple institutions and clinics. It is important to note that based on the results of the current study, the real-time feedback tool should not be considered a replacement for basic training in landmark identification and palpation techniques for all users. While the potential of using the software as an educational tool exists, some novice examiners, as observed in the current study, may require additional instruction and practice as an adjunct to the use of the tool.

5.4. Future Directions

Further research examining the use of real-time feedback software to improve marker placement consistency should be guided by the previously addressed limitations to the current study. First, future studies should incorporate a sample of intermediate or expert examiners to investigate the effect of the feedback tool on examiners with considerable clinical anatomy experience. For example, prior research has shown that within- and between-examiner consistency of experienced examiners and physical therapists still requires improvement (Kadaba et al., 1989; Schwartz et al., 2004). In support of this finding, Ferrari et al. (2008) reported up to 30° of error between various data collection methods performed simultaneously on a single subject, despite each method being carried out by a corresponding expert. Similarly, between-examiner studies using multiple clinic locations have also reported errors in excess of 30° for certain joint angles among experienced examiners collecting gait data on the same subject., The examiners averaged 5.0 years of clinical gait analysis experience and 11.8 years in a clinical setting (Gorton et al., 2009).

Despite having more experience with gait kinematic data collection, it is possible that experienced examiners have developed individual tester bias, which may be addressed with real-time marker placement feedback. Previous studies have relied upon experienced examiners to guide standardization protocols, marker placement training, and marker placement devices for novice users (Gorton et al., 2009; Kalkum et al., 2016; Leigh et al., 2014; Noehren et al., 2010). Therefore, it is in the best interest of researchers to ensure the examiners responsible for training new users are consistent relative to one another.

Second, including examiners from multiple sites would provide insight to the feasibility of incorporating real-time feedback for the development of multi-centre collaboration. It is also

important to monitor the experienced examiners over time to determine whether any effect of the feedback tool is maintained from one session to the next, or if the group of users revert to the same placement habits they possessed prior to first receiving feedback. This proposed study would be similar to the current protocol, however, the inclusion criteria for the examiners would require a pre-determined number of years with prior experience collecting gait analysis data in either a research or clinical setting. However, the examiners should belong to different clinics or labs, and potentially come from different training backgrounds related to the study of human gait.

Third, to further understand the educational benefit of the feedback tool, research concerning new methods to reduce the potential learning effect introduced by the examiners making a second visit to the laboratory is necessary. Specifically, in the current study it is possible that marker placement for the PRE2 session was aided by a learning effect stemming from the day one marker placement that occurred one week prior. Therefore, to reduce the learning effect, a second runner could be incorporated into the data collection protocol. The same runner would be used for each examiner on day one, however on day two, one week later, examiners would place markers on the second runner instead. Having the examiners collect 3DGA data on an additional runner for follow-up may reduce the learning effect of the baseline marker placement session that may be present when utilizing only one runner for both sessions.

Previous research has shown that gender differences exist in lower extremity alignment and lower extremity kinematics during the stance phase of running (Ferber, Davis, & Williams, 2003; Horton & Hall, 1989; Phinyomark et al., 2016). Thus, as an alternative methodology to incorporate a second runner, future research may implement a protocol that uses one male runner and one female runner. By having markers placed on a male runner during day one, and a female

on day two, this protocol would not only reduce the possibility of a learning effect between sessions, but also give insight to any gender differences surrounding marker placement consistency.

The length of time between a baseline and follow-up session for most research studies can range from one or two weeks to over one year (Beaulieu et al., 2010; Gaudreault et al., 2011; Sartor et al., 2012; Steinwender et al., 2000; Watari et al., 2016). To further test the longevity of the real-time feedback tool, a longitudinal study involving multiple follow-up sessions occurring at longer time intervals will be representative of various protocols observed throughout the literature incorporating 3DGA. Using the same experience level of examiners and a single runner, future research should extend the time-to-follow-up between day one and day two. Not only is increasing the time interval occurring between sessions more representative of the literature, but it will also help to reduce any potential learning effect in conjunction with previously noted protocol adjustments. A longer time interval also allows for multiple follow-up sessions to be collected, for example the same 12 examiners could visit the lab one week, one month, six months, and one year following the baseline session. Five total sessions, each with pre- and post-feedback conditions will provide more time points for data analysis and the ability to track any trends in marker placement consistency over time. To isolate the role of the marker placement feedback tool, the examiners should not receive any additional training in marker placement during this time interval, beyond using the feedback tool. As another addition to the protocol, the 12 novice examiners could be randomly assigned into two groups, with one group receiving extensive formal training in marker placement and landmark identification from a trained expert prior to the baseline session, similar to Leigh et al. (2014). By comparing the trends in the pre-feedback marker placement consistency over time between the trained and

untrained novices, researchers may determine if the skills acquired during the initial training session are maintained over the period of one year. If the placement consistency of the trained novices degrades over time and becomes no different than the group of untrained novices it might indicate the feedback tool exceeds the capabilities of a standard marker placement training session for improving marker placement consistency over an extended period of time.

Regardless of the specific details, a longitudinal study design will track the marker placement consistency of an individual examiner, or group of examiners, to determine if real-time feedback continues to have a positive influence on consistency.

Finally, further development, diversification, and specific partitioning of the reference database has the potential to improve the quality of marker placement feedback. In its current state, the feedback tool references a database consisting of healthy adults, with no known pathologies that could affect lower extremity morphology (Osis et al., 2016). As noted by these authors, one of the strengths of the feedback tool is that the reference database can be altered to include previous static trials belonging to individuals with various joint pathologies or lower extremity deformities to better represent the individual that is being examined. By increasing the variety of subjects within the database, the examiner may be able to select specific iterations depending on the current subject's morphological characteristics. A larger reference database would also allow the feedback tool to select a more representative cohort for determining the IQRR for each marker location. However, it is important that any static trials added to the database are collected using the marker placement tool as a guide.

5.5. Conclusion

The findings of the current study show a real-time feedback tool's ability to improve consistency of marker placement for a group of novice examiners, leading to improved

consistency in 3DGA data. The results build upon previous attempts to address placement consistency, as the methodology does not require an experienced examiner to make initial landmark identification for the baseline or to set-up and calibrate an external device. In addition, the marker placement feedback is received immediately following the collection of a static trial, making the tool practical in a clinical setting. While further refinement of the tool is encouraged, the study outcome demonstrates its benefit in both a clinical and research setting. The improved consistency observed on day two further highlights the lasting benefit of the software when incorporated into a standard 3DGA protocol involving baseline and follow-up data collections.

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Appendix A

Conjoint Health Research Ethics Board
Research Services Office
3rd Floor MacKimmie Library Tower (MLT 300)
2500 University Drive, NW
Calgary AB T2N 1N4
Telephone: (403) 220-7990
chreb@ucalgary.ca

Consent Form

TITLE: Methods to improve the reliability of biomechanical gait kinematic data.

SPONSOR: National Science and Engineering Research Council of Canada

**INVESTIGATORS: Dr. Reed Ferber (403) 210-6468
AJ Macaulay**

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Take the time to read this carefully and to understand any accompanying information. You will receive a copy of this form.

BACKGROUND

Biomechanical gait analysis is one of the most ubiquitous research methods for analysing sport performance or evaluating pathologic gait. However, incorrect marker placement results in errors.

We believe that in order to improve biomechanics research, new approaches must be developed such as software to provide realtime feedback on marker placement locations. Our published research has developed a “gold-standard” marker set [Osis et al., 2014], based on a sample of n=400, and using one Expert tester to minimize this limitation and develop realtime feedback software.

This is a repeated measures study evaluating this new software-based approach. We hypothesize that realtime feedback, using our software program, can significantly reduce marker placement errors.

10 subjects, aged 18-28 years, who meet a set of defined criteria, will be recruited and invited to participate in this study.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of this study is to evaluate and inform the development of robust training methods and software tools for biomechanists.

WHAT WOULD I HAVE TO DO?

Step 1 – Inclusion Criteria

- In order to participate in the study, you will have to taken the following courses: (1) KNES 259: Human Anatomy & Physiology I, (2) KNES 263: Quantitative Biomechanics, and either currently be enrolled in or have completed (3) KNES 463: Advance Techniques In Biomechanics.

Step 2 - Baseline Testing (60 minutes)

- You will receive a brief training session from Dr. Ferber regarding proper marker placement for kinematic gait analysis.
- You will then be asked to place small retro-reflective markers on specific anatomical landmarks of the ankle, knee, and hip for one subject.
- A 1-second static trial will be collected and a software program will demonstrate where your markers are placed, relative to a model of expected placement locations.
- You will have the opportunity to relocate those markers that lie outside of an error threshold and a second static trail will be collected.

Step 3 – Repeat Visit (45 minutes)

- Approximately 1-week later, you will be asked to come back to the laboratory and a portion of the procedure will be repeated.
- You will then be asked to place small retro-reflective markers on specific anatomical landmarks of the ankle, knee, and hip for one subject.
- A 1-second static trial will be collected and a software program will demonstrate where your markers are placed, relative to a model of expected placement locations.
- You will have the opportunity to relocate those markers that lie outside of an error threshold and a second static trail will be collected.

WHAT ARE THE RISKS?

There is the possibility of an allergic response to the double sided adhesive tape used to secure the retro-reflective markers.

WILL I BENEFIT IF I TAKE PART?

If you agree to participate in this study there may or may not be a direct benefit to you. If you are in the study, it is because you have been identified as having a minimal university-level of biomechanics education and training. Participation in this study may provide you with a deeper understanding of the practices and theories of biomechanical gait analysis.

DO I HAVE TO PARTICIPATE?

Your participation in this study is voluntary and you may withdraw from the study at any time without jeopardizing your health care. If you choose to withdraw your participation, please inform Dr. Reed Ferber in one of three ways: 1) in person, 2) by calling 403-210-6468, or 3) via e-mail at: rferber@ucalgary.ca

If new information becomes available that might affect your willingness to participate in the study, you will be notified as soon as possible.

WHAT ELSE DOES MY PARTICIPATION INVOLVE?

There are no additional expected commitments other than those stated above.

WILL I BE PAID FOR PARTICIPATING, OR DO I HAVE TO PAY FOR ANYTHING?

Participation is on a voluntary un-paid basis. There are no anticipated costs to your involvement in this study. The location of the study is at the Human Performance Laboratory in the Faculty of Kinesiology at the University of Calgary.

WILL MY RECORDS BE KEPT PRIVATE?

Your information will be kept confidential and secure. This consent document will be stored electronically on a password protected computer and accessible to Dr. Ferber and assigned study personnel. You will be identified by a study number.

IF I SUFFER A RESEARCH-RELATED INJURY, WILL I BE COMPENSATED?

In the event that you suffer injury as a result of participating in this research, no compensation will be provided to you by the National Science and Engineering Research Council of Canada, the University of Calgary, Alberta Health Services or the Researchers. You still have all your legal rights. Nothing said in this consent form alters your right to seek damages.

SIGNATURES

Your signature on this form indicates that you have understood to your satisfaction the information regarding your participation in the research project and agree to participate as a participant. In no way does this waive your legal rights nor release the investigators or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardizing your health care. If you have further questions concerning matters related to this research, please contact:

Dr. Reed Ferber (403) 210-6468

If you have any questions concerning your rights as a possible participant in this research, please contact the Chair, Conjoint Health Research Ethics Board, University of Calgary at 403-2207990.

Participant's Name

Signature and Date

Investigator/Delegate's Name

Signature and Date

Witness' Name

Signature and Date

The University of Calgary Conjoint Health Research Ethics Board has approved this research study.

A signed copy of this consent form has been given to you to keep for your records and reference.

Appendix B

Permission granted for Figure 2-1.

Thu 04-13, 12:59 PM
Charles Andrew John Macaulay

Dear Mr. Macaulay:

It is our pleasure to grant you permission to use the ASME **Figure 5** from "Application of the Joint Coordinate System to Three-Dimensional Joint Attitude and Movement Representation: A Standardization Proposal," by G. K. Cole; B. M. Nigg; J. L. Ronsky; M. R. Yeadon, J Biomech Eng. 1993; Vol. 115, cited in your letter for inclusion in a Master's Thesis entitled The use of real-time feedback to improve kinematic marker placement consistency among novice examiners to be published by The University of Calgary.

As is customary, we request that you ensure full acknowledgment of this material, the author(s), source and ASME as original publisher. Acknowledgment must be retained on all pages printed and distributed.

Many thanks for your interest in ASME publications.

Sincerely,

Publishing Administrator
ASME

Appendix C

Permission granted for Figure 2-4.

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Appendix D

MARKER PLACEMENT – FULL GAIT ANALYSIS

1. Foot:

- First Metatarsal Head (RMH1): Place a marker on the most medial point of the 1st metatarsal head.
- Fifth Metatarsal Head (RMH5): Place a marker on the most lateral point of the 5th metatarsal head.

2. Shank:

- Head of the Fibula (RFIB): Feel for the most prominent point of the bone on the lateral aspect of the shank (~ 2-4cm below the knee joint line).
- Tibial Tuberosity (RTUB): Feel for the most obvious point of bone on the anterior tibia, below the distal point of the patella.
- Lateral Malleolus (RMAL): Place a marker over the most lateral point of the ankle, making sure the marker is directly lateral (not up, not down, etc.).
- Medial Malleolus (RMAM): Place a marker over the most medial point of the ankle. The marker is usually slightly higher than the lateral marker.

3. Thigh:

- Lateral Knee (RKNL): Have the subject bend and straighten their knee while feeling for the dip or gap between the femur and tibia; it is most obvious when the knee is bent. Have the subject straighten their knee and place the marker on the lateral joint line.
- Medial Knee (RKNM): Feel for the same gap on the medial side of the knee. Place a marker on the most medial point of the joint line. The medial marker is usually slightly lower than the lateral marker.

4. Pelvis:

- Shell (RPSI, LPSI, VSAC): The two top markers on the triangle shell are lined up at the level of the PSIS.
- Iliac Crest (RILC): Place a marker at the top level of the iliac crest bilaterally near the, midline of the body (when looking from the side), approximately vertical to the greater trochanter.
- ASIS (RASI): Follow the iliac crest down the front of the pelvis and feel for a little “hook” of bone with your thumb. Place a marker directly over the point.
- Greater Trochanter (RGTR): If the trochanter is not obvious, have the subject internally and externally rotate their hip and feel for the trochanter moving under your fingers. Place the marker on the most obvious point of bone while the subject is standing straight and evenly on both feet.

Appendix E

Mean Joint Angle Data by Participant

Ankle Frontal Plane Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-4.3182	-6.0830	-7.3505	-6.4383
002	-5.6143	-5.1904	-6.8266	-7.3097
003	-6.4790	-7.5899	-9.5832	-9.3007
004	-8.8873	-9.4241	-7.4098	-8.0146
005	-9.4887	-9.1525	-7.9399	-8.5612
006	-9.6699	-8.8312	-6.0698	-7.5356
007	-8.1369	-9.6228	-5.1591	-6.1155
008	-7.3750	-7.8835	-6.3207	-6.0962
009	-7.2646	-6.8772	-7.3331	-7.4475
010	-6.3066	-6.7427	-7.8650	-7.4723
011	-6.7778	-7.0186	-6.1313	-5.9616
012	-8.2374	-7.0821	-5.8127	-5.3522

Ankle Frontal Plane Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-4.6212	-5.0169	-5.3311	-5.4250
002	-5.3231	-5.5810	-5.2891	-6.3774
003	-6.2891	-6.7431	-7.0109	-6.5583
004	-6.3114	-5.4637	-6.5072	-5.4483
005	-7.2417	-7.8989	-6.8123	-6.6823
006	-9.1621	-8.4463	-7.7968	-8.6176
007	-8.3491	-7.6323	-6.6316	-7.1367
008	-8.1090	-7.2719	-5.4427	-6.0095
009	-6.8017	-5.5439	-6.7273	-6.0251
010	-6.2337	-6.3752	-6.8985	-7.5458
011	-6.5471	-5.5130	-4.7791	-5.0616
012	-7.5315	-6.2251	-4.6477	-5.1764

Ankle Transverse Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	13.6856	-0.9935	-19.0312	-13.4588
002	-1.3565	-0.0577	-6.5717	-5.0425
003	-0.3040	-5.9633	-11.5658	-11.9410
004	-0.1220	-12.3336	-6.3143	-7.1134
005	-6.8475	-3.4779	-5.6876	-9.7853
006	-10.4672	-9.9480	2.0370	-9.8968
007	-4.2944	-6.0720	1.2471	-0.0395
008	-1.7465	-2.7600	-6.4324	-4.2529
009	2.1947	-4.3594	1.9054	-6.9738
010	2.8805	-1.5979	-10.7993	-10.2398
011	-2.4613	-7.5587	-7.7914	-7.9896
012	-10.2964	-9.4139	-1.0629	-7.5636

Ankle Transverse Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	3.3791	2.9623	-7.6561	-9.9047
002	-0.3798	-0.9298	-1.1217	-2.9181
003	-2.1855	-2.0733	-1.6698	-6.3685
004	-4.6502	-3.6621	-2.5005	-2.3272
005	-2.6911	-8.3935	-4.8730	-6.1010
006	-7.8754	-6.6657	-3.7148	-2.1757
007	-0.3139	-0.8708	-4.7784	-4.3675
008	-3.8989	-3.7250	-1.1695	-1.4197
009	-5.0679	-1.7870	-0.7979	-1.8996
010	-1.2273	-5.5736	-6.0961	-7.3889
011	3.1163	3.5924	-1.7005	0.3376
012	-4.6968	-3.5978	-4.9630	-5.7859

Ankle Sagittal Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	6.4836	2.6804	4.9266	7.6923
002	5.2172	6.3911	3.6284	0.7848
003	4.8837	4.1239	1.8600	0.5114
004	1.5148	1.0631	3.5432	0.3973
005	-0.5759	1.0099	-0.0334	-0.3751
006	-1.2585	-2.5598	2.8488	-2.9299
007	5.3703	-0.1838	2.6134	-0.8141
008	0.5270	2.4176	0.3314	2.1085
009	-1.6580	-1.1469	2.8318	2.0788
010	-0.5160	3.5876	-0.3307	0.0978
011	-6.0733	-5.9573	6.3146	4.9895
012	-1.3071	0.2347	-0.1955	1.4253

Ankle Sagittal Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	4.5563	5.2123	5.7287	5.6975
002	3.5411	4.3585	4.3278	4.2998
003	3.7053	4.4236	3.9153	5.2377
004	2.9467	2.3109	4.4914	4.9999
005	1.5021	2.8402	2.8681	3.4396
006	0.7141	-0.9078	1.4993	0.3494
007	4.5855	3.3829	3.4279	3.5375
008	-0.0271	1.1418	2.5367	1.5239
009	-0.8198	0.6626	2.4333	2.5190
010	0.1617	1.0721	-0.9415	-1.0937
011	-3.4815	0.0542	5.0500	3.5656
012	-3.2442	-2.1025	-0.0429	2.5639

Knee Frontal Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-2.4959	3.4692	16.4709	15.2458
002	6.4713	5.7762	7.1544	8.7023
003	5.7259	5.9604	11.1982	12.0781
004	6.7852	11.7004	10.6226	8.8990
005	6.7453	4.0885	6.1906	8.7721
006	12.2254	11.8991	6.0934	10.3947
007	10.5290	11.6879	5.6409	5.3325
008	7.8372	8.4070	10.6464	10.7342
009	5.8949	7.8949	3.3509	8.7834
010	9.8116	9.2010	10.8251	10.8367
011	8.2199	6.2963	8.9912	9.0620
012	12.1106	11.4232	5.5662	9.5016

Knee Frontal Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	8.1398	7.2391	11.4300	12.4736
002	7.8052	8.0037	8.6612	9.0276
003	9.7737	8.2114	9.9059	11.3498
004	8.2226	11.7073	9.1457	7.4102
005	9.3996	11.6894	10.5111	12.6963
006	17.6642	17.4879	12.1914	11.5436
007	6.9763	8.9261	10.9034	11.8121
008	15.3860	13.9652	6.9949	7.5069
009	11.4121	7.6777	11.3129	11.4371
010	14.6028	11.5804	13.6906	14.2103
011	7.0630	6.1816	6.5648	5.1563
012	12.0409	11.6792	6.7302	8.9125

Knee Transverse Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-0.2038	5.7485	22.6455	15.8712
002	12.1353	4.5431	9.5641	8.7890
003	21.0924	11.3760	27.1029	25.0583
004	0.5980	7.4051	7.9032	6.4122
005	8.3295	1.9168	15.0600	16.8103
006	11.4316	11.8903	10.0373	10.1446
007	5.3328	19.6052	6.7983	7.1575
008	6.6607	12.4948	15.2352	12.8061
009	19.2533	9.3051	12.4478	19.0984
010	17.1098	11.3860	5.8232	5.3003
011	11.8446	-1.4212	22.1315	-6.4475
012	15.7964	9.3452	3.9628	9.5505

Knee Transverse Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	9.2041	10.0756	15.3998	18.6070
002	13.4770	14.8950	12.4724	12.4731
003	23.0701	20.5465	23.0386	18.1852
004	19.1148	22.4472	17.4024	16.1780
005	14.3735	16.1863	13.3646	21.4061
006	33.8848	31.0716	16.5412	9.0048
007	11.8889	11.6001	18.0791	20.4909
008	22.6804	16.5439	16.1114	16.0314
009	17.1845	8.1931	21.2585	26.2675
010	24.7479	15.6247	22.5249	23.6250
011	15.6839	15.3756	24.7910	6.3843
012	28.7886	19.2487	4.9125	25.7090

Knee Sagittal Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	43.0417	42.1616	35.9346	36.3106
002	38.9334	37.9657	37.0045	38.7463
003	38.1773	37.2191	40.0103	40.6982
004	35.8602	38.8157	44.2684	43.6025
005	43.3227	40.4168	38.4430	41.2294
006	46.1615	46.8520	49.1052	50.1875
007	39.7197	41.2512	41.5205	43.2159
008	45.5725	45.4626	44.4061	44.3149
009	45.4010	45.2939	42.2203	41.5656
010	39.8741	40.9884	40.4178	42.4332
011	51.8880	50.1880	30.1134	35.0507
012	41.6027	41.3823	41.0392	41.6635

Knee Sagittal Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	43.4473	41.0147	37.3121	35.9120
002	36.5889	34.9438	37.1687	37.5555
003	40.9499	39.9896	42.2616	39.4091
004	35.8379	40.6565	44.9315	41.8476
005	45.6266	41.5317	38.8366	40.4141
006	47.3219	47.3593	49.8284	51.4841
007	40.9813	42.0994	43.1444	41.2810
008	48.0341	47.7848	43.1686	43.5110
009	44.1465	43.2777	44.2656	43.0284
010	41.1096	42.5245	42.4592	43.4527
011	53.6167	47.7171	29.0362	34.0491
012	41.8654	40.5521	41.3183	37.3071

Hip Frontal Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-1.1866	-1.8738	-2.3447	-4.2528
002	-0.3068	-3.4442	-3.1681	-5.1105
003	2.0314	-2.3684	-0.0713	-1.4296
004	-7.0438	-5.4659	-4.8457	-3.6358
005	-1.3712	-2.0391	-0.0276	-1.3886
006	-3.4705	-3.3865	-2.8458	-3.2890
007	-6.3762	-2.4033	-4.1237	-1.8817
008	4.4511	-0.5893	-0.9496	-2.6871
009	-0.1400	-1.9709	-1.3561	-0.5731
010	-2.2746	-4.0522	-3.4605	-5.2820
011	-2.4186	-4.2669	-7.1648	-6.4450
012	-3.6214	-4.8265	-3.0750	-4.3195

Hip Frontal Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-4.0626	-3.6871	-3.8185	-3.3033
002	-5.1130	-3.8946	-1.8204	-2.3802
003	-1.0261	-0.2833	-1.6136	-2.2303
004	1.2367	-0.6989	0.4368	-0.3226
005	-2.1337	-1.8537	-3.3121	-2.0494
006	0.3834	-1.3529	-0.3654	-3.6337
007	1.0344	-2.1462	0.9597	-2.7965
008	-5.8518	-3.8164	-2.4592	-1.4217
009	-2.1906	-4.2203	-0.8529	-0.0409
010	-4.2921	-2.3933	-2.7573	-0.4419
011	3.3439	1.2179	4.9692	-3.8663
012	-0.5631	-2.9443	-5.8913	-0.0517

Hip Transverse Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-8.6124	-3.4376	-9.5512	-5.4558
002	-12.1640	-5.1158	-3.6325	-2.8842
003	-19.3082	-9.4158	-18.4020	-16.3833
004	-0.2575	-1.9775	-2.8759	-1.6621
005	-14.4017	-2.5765	-12.6615	-14.7868
006	-11.1734	-10.2264	-10.8350	-7.8268
007	-6.4100	-20.4791	-4.9907	-5.3576
008	-3.2177	-10.7638	-9.9236	-7.0805
009	-17.7460	-3.8973	-13.7152	-17.1515
010	-14.1375	-5.5622	-4.7741	-1.0082
011	-20.0309	-4.2921	-13.1307	9.8606
012	-11.8741	-4.6903	-3.0651	-3.9027

Hip Transverse Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	1.9654	-2.8821	1.6133	1.8181
002	2.2861	0.5431	-2.6816	-4.2951
003	-9.3855	-7.5161	-13.2509	-3.8138
004	-2.4818	-5.3155	-5.2795	-2.8213
005	4.5626	0.5915	2.1466	-2.5480
006	-15.7841	-13.4024	-5.0559	0.0647
007	2.8109	4.0807	-5.2965	-6.5266
008	-12.4726	-3.8746	-3.4902	-4.4457
009	-7.1016	0.3822	-10.9635	-12.4008
010	-6.8049	-3.9480	-6.1272	-11.0998
011	-0.2685	0.2676	-10.8326	5.9964
012	-14.0803	-4.4247	7.8667	-8.7050

Hip Sagittal Plane				
Left Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-26.0620	-16.9795	-16.6119	-11.4448
002	-9.7504	-7.9515	-11.6760	-10.1304
003	-15.1205	-11.3155	-11.8781	-11.4570
004	-11.4963	-12.9723	-18.5802	-15.5956
005	-12.5995	-10.4039	-11.3701	-11.6339
006	-13.4282	-12.9619	-18.4653	-15.8322
007	-18.2768	-14.2956	-23.7210	-14.0032
008	-24.7999	-14.1399	-13.5625	-13.7465
009	-18.3120	-16.1091	-15.2333	-17.1893
010	-7.5649	-11.7738	-12.2735	-14.8849
011	-26.4961	-18.4571	-13.7344	-11.6358
012	-13.4792	-12.3476	-23.4242	-17.9360

Hip Sagittal Plane				
Right Limb				
Participant	PRE1	POST1	PRE2	POST2
001	-26.1269	-15.4554	-16.0584	-10.1848
002	-7.7849	-5.7736	-12.4379	-9.8982
003	-15.6332	-11.5722	-12.0890	-9.7764
004	-9.8840	-13.5015	-18.1596	-14.2006
005	-12.7993	-9.6131	-10.0869	-9.1322
006	-13.6075	-12.6697	-17.4710	-15.3576
007	-18.2102	-13.1511	-25.4593	-13.5596
008	-27.8154	-14.6749	-11.9853	-12.0421
009	-15.3227	-13.5513	-15.9609	-17.6641
010	-9.3077	-11.8483	-14.5394	-14.7908
011	-26.8104	-16.7698	-7.3322	-9.0036
012	-11.9681	-10.0535	-21.1712	-14.3037