Department of Biomedical Engineering

Validation of a Novel 2D Motion Analysis System to the Gold Standard in 3D Motion Analysis for Calculation of Sagittal Plane Kinematics

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Decleration of Authenticity

This thesis is the result of the author's original rsearch. It has been composed by the author and has not been previously submitted for examination wich has led to the award of a degree.

Signature: Lindsay Clarke Date: 13/08/13

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Abstract

Movement analysis is a key component of clinical diagnosis, treatment prescription and follow up of gait disorders. Instrumented 3D gait analysis is often financially and technically inaccessible in clinical environments. Other established methods of gait analysis include video and visual observation scores; however these techniques rely on subjective clinical expertise. The aim of this study is to compare a bespoke video based 2D motion analysis system (VOHM) to the 3D gold-standard.

Ten participants (5 male, 5 female, mean age 23.3 ± SD2.8 years) with no history of gait disorders volunteered for this study. Participants were asked to walk at a self-selected speed until a minimum of 5 clean trials had been recorded. Digital video (Basler Ace series) and a 12 camera Vicon T-series 3D motion capture system were used to synchronously capture participants gait (100Hz). Parameters under investigation were shank to vertical angle, thigh to vertical angle, and knee joint centre flexion angle. Data processing was carried out using Nexus 1.8.2 for Vicon and VOHM for video data. Data analysis was performed using Matlab, SPSS and Microsoft Excel.

Intra class correlation coefficients (ICC) showed strong significant agreement ($p<0.001$) between measurement systems for all parameters: ICC = 0.99(SHANK), 0.96(THIGH), 0.96(KJC). Spearman's rho correlations for SHANK, THIGH and KJC showed very strong (0.99, 0.93, 0.94 respectively) significant agreement ($p<0.001$). Linear regression analysis also showed significant ($p<0.001$) agreement with R^2 values for SHANK, THIGH and KJC of 0.98, 0.95 and 0.97, respectively. Bland-Altman plots for each parameter indicated a high level of agreement.

Statistical analyses revealed excellent agreement between Vicon and VOHM for analysing human gait. As a result, VOHM may be recommended for use in the clinic providing that only the parameters under investigation in this study are considered.

1. Introduction

1.1 History of Motion Capture

The science of Human Movement Analysis has matured to its current level over several decades and is now considered as an essential tool for biomechanical research and clinical diagnosis of gait and movement abnormalities (Gage 1993; Cook *et al.* 2003; Lofterod *et al.* 2007).

An interest in the way humans move has been apparent since the early 1800s (Sturman 1999). However, the lack of knowledge and equipment prevented motion capture systems becoming commercially available until the 1970s. Advanced motion capture systems were then introduced into the field of biomechanics in the early 1980s (Sturman 1999). With the introduction of computer generated animation in the games and movie industries the technology advanced rapidly in the 1990s and 2000s. Since then technology has been continuously improving, allowing more accurate, precise and accessible motion capture and analysis.

This study aims to further increase the accessibility of quantifiable, automated motion analysis by validating a piece of bespoke 2D motion analysis software against the gold standard in 3D motion analysis.

1.2 Introduction to Motion Analysis

There are many aspects of biomechanical research, medicine and rehabilitation which can benefit from the information generated by motion capture. However, one of the most researched areas within movement analysis is the analysis of human gait. Whittle (1996) stated that advances in four areas of science contributed to the development of gait analysis: kinematics; kinetics; electromyography (EMG) and engineering mathematics. Kinematics describes the movement of a subject during walking and would be described by parameters such as the flexion angle of a given joint. Kinetics is concerned with the forces generated during locomotion, such as the external ground reaction force (GRF) and internal forces. EMG is a method of electronically measuring muscle activity by either attaching electrodes to the skin or placing fine wire electrodes directly into the belly of a muscle. A combination of all of these measurements can give a comprehensive description and analysis of human gait. Gait is often analysed in cycles, with different terminology used to describe different stages of the cycle. Figure 1 shows a full cycle of the right leg, from one initial foot strike to the next. The cycle is often divided into phases, in order to better

describe the events occurring. The simplest division is to separate the cycle into stance phase, when the foot is in contact with the floor and swing phase, when the foot is not in contact with the floor. Stance phase can be further subdivided into first double support, when both feet are initially on the floor, single support, when only one foot is on the floor and second double support, when the opposite foot is back in contact with the floor. The point at which the stance phase ends is called foot-off (sometimes referred to as toe-off). Swing phase is relatively long in comparison to stance phase and hence is also often subject to further subdivision. Swing is often divided into three sub phases of equal duration; initial swing; mid swing and terminal swing (Baker 2013; Lim *et al.* 2007; figure 1).

The gait cycle is often normalised to 100% and certain events are expected to occur at certain time percentages of the cycle. For example, foot-off is expected to occur at approximately 60% of the gait cycle. Deviations from the time at which these events occur may help to indicate an abnormality or impairment.

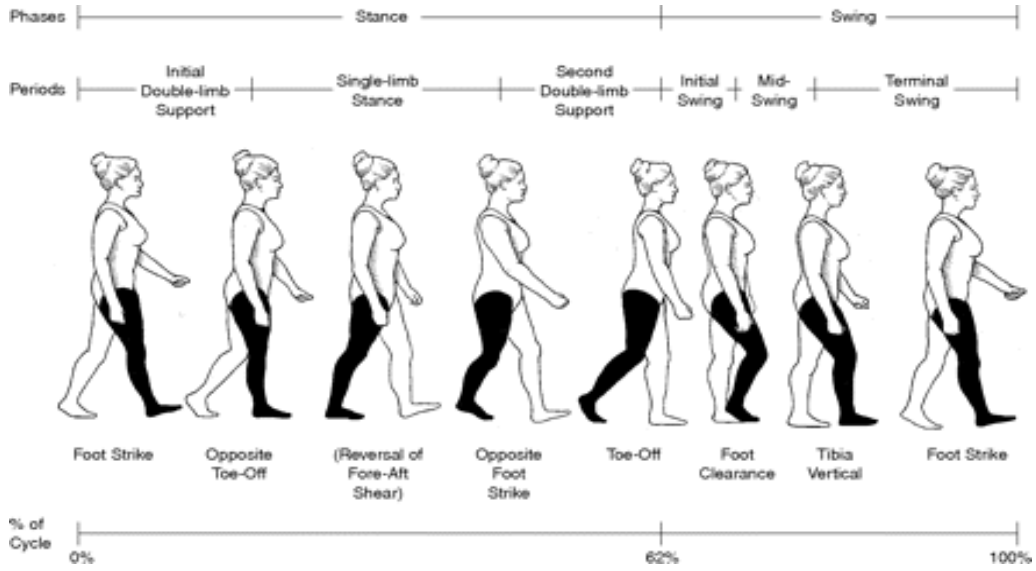

Figure 1. Stages of the gait cycle (Lim *et al.* 2007).

Gage (1993) describes the 5 prerequisites of normal gait to be 1) stance phase stability, 2) swing phase clearance, 3) foot preposition in terminal swing, 4) adequate step length and 5) energy conservation. In the case of many patients with movement disorders it is likely that one or more of these prerequisites is not being met. A great number of patients may then find themselves requiring walking aids or may even end up in a wheelchair if the pathology is not corrected. Alongside other services such as medical imaging and physical examinations, gait analysis should be considered an essential component of patient management for such individual (Cook *et al.* 2007; Gage 1993). An

experienced clinician or biomedical engineer can perform gait analysis on the patient which will give a detailed description of the gait abnormalities. This can aid physicians in the treatment decision making process. This also applies in rehabilitation. For example, in the case of stroke patients, gait analysis can determine the effectiveness of physiotherapy or other treatments such as walking aids. Likewise for amputees, gait analysis can help to determine the correct fitting and alignment of the prosthesis. The more we can learn about human gait, the more we can be aware of possible problems and abnormalities and hence how to better treat them.

1.3 Overview of Motion Capture Systems

Many different types of systems and methods exist for analysing movement. These include simple visual or digital video observation of a patient, 2D computer analysis of video footage and fully instrumented three dimensional (3D) analysis. Largely due to the expensive nature of some of the state of the art motion capture systems, and the associated high levels of technical expertise needed to operate such systems and distil useful clinical information from the data, a number of visual analysis methods have been developed. These can allow physicians to score patients on their gait, giving a quantifiable outcome without the need for an expensive and often technically inaccessible system. One step up from visual assessment would be the analysis of videotape footage using a computer programme. There are a number of software packages available which are capable of calculating kinematic data from recorded walking trials. However, there is little clinical validation of these packages and many require manual digitisation of each individual frame of the gait cycle. This process is time consuming and subjective, and is therefore likely to impact on the validity and accuracy of the gait analysis. Some software packages, such as Simi Aktysis (Simi 2013), provide automatic marker recognition and real time kinematic data calculations during playback. However to the author's knowledge this software has never been validated for clinical use. The most common alternative to visual and videotape analysis is fully instrumented 3D analysis. There are a range of 3D motion capture systems available, a number of which have been validated for clinical use (Barker *et al* 2005; Mazumder *et al.* 2011). These systems tend to be more accurate and reliable for a number of reasons. Some are purpose built for clinical motion capture and often implement multi-camera set ups. This increases the capture volume and also increases the accuracy of marker detection. The systems often come with hardware and software components, an advantage of this being that the software was written to work with a

specific system. In the case of many 2D analysis systems, the software is written to work with a number of hardware options, and therefore may not be ideally suited to all available options. Section 1.3.1 through section 1.3.7 provides a more comprehensive overview of the various techniques and systems that are often used for clinical gait analysis, along with a description of how instrumented systems work.

1.3.1 The Gross Motor Function Classification System (GMFCS)

Palasino *et al.* (1997) set out to develop a system which was capable of classifying the gross motor function of children with cerebral palsy. After examining current assessment systems, such as the Gross Motor Function Measure (GMFM) (Russell *et al.* 1989), it was found that there were large variations and overlap between groups, particularly in patients which more severe involvement. The GMFM implemented a 3 level classification system which the authors deemed inappropriate and so a 5 level system was suggested. The system demonstrated good inter rater reliability and confirmed that physical therapists could accurately classify a child's motor function. The GMFCS has been widely validated for use within the clinical setting for classifying the motor function of children with CP (Bodkin *et al.* 2003; Palisano *et al.* 2006; Rosenbaum *et al.* 2002).

- Level I – "Walks without restrictions; limitations in more advanced gross motor skills".
- Level II – "Walks without assistive devices; limitations walking outdoors and in the community".
- Level III – "Walks with assistive mobility devices; limitations walking outdoors and in the community".
- Level IV – "Self mobility with limitations; children are transported or use power mobility outdoors and in the community".
- Level V – "Self mobility is severely limited even with the use of assistive technology".

Wood and Rosenbaum (200) stated that the GMFCS can be validated for clinical use and is capable of describing the motor activities of children with CP. They also reported that the GMFCS is capable of detecting change in motor activities following an intervention. Despite these validations, the GMFCS is still not a suitable substitute for 3D analysis as results remain to be qualitative and rely on technical expertise.

1.3.2 The Edinburgh Visual Gait Score (EVGS)

The EVGS is a widely used visual observation score which can be used to quantify gait assessments in patients with CP. The EVGS was developed by Read *et al.* (2003) and was established as a simple system for assessing gait by observation. Seventeen clinically relevant parameters which are indicative of pathological gait were investigated. Deviations from normal joint angle ranges were subdivided into two categories depending on the degree of severity. The scoring system is as follows: 0 = normal (mean ± <1.5 SD); 1 = moderate deviation (1.5-4.5 SD from mean); and 2 = marked deviation (>4.5 SD from mean). Therefore, the maximum total score for one limb would be 34 if the subject presented with a marked deviation for each parameter.

Further testing of the reliability of the EVGS showed good intraobserver reliability and a high correlation of EVGS scores with fully instrumented 3D data for >64% of observations. It was also proven that the EVGS was capable of detecting postoperative change, with a decrease in the score following surgery in all but one subject. The validity of the EVGS was further proven by Gupta and Raja (2012) who confirmed that it can be used to evaluate the effect of orthopaedic surgical intervention in children with CP.

While the EVGS has been proven to be reliable and capable of detecting post-operative change, it has been proven that it cannot act as an appropriate substitute for 3D analysis (Kawamura *et al.* 2007; Ong *et al.* 2008).

1.3.3 How Instrumented Motion Capture Works

The majority of instrumented motion capture systems will implement the use of markers in order to track anatomical landmarks and allow the system to calculate joint centres. This will allow the software to accurately calculate kinematic data. 2D systems can use markers as simple as a paper circle, which the software can track using (amongst others techniques) automatic detection of image region properties, masking and blob analysis methods. It may be advised that when using video camera recording for 2D motion analysis that the camera records at a minimum of 100Hz; this is slightly higher than a recreational video camera which ensures that the video will capture discrete events of the gait cycle such as foot contact or foot-off by reducing ambiguity between frames. This is of major importance when using certain types of 2D analysis software as manual digitisation of each frame of video is required in order to calculate any kinematic parameters.

Three dimensional motion capture systems tend to be more advanced than 2D systems in a number of ways; both the markers and the software used to analyse the data are likely to be more complex. For advanced 3D motion capture systems, markers can be classed as active or passive. Passive markers are retroreflective which allows them to reflect light strobed from the cameras, whereas active markers emit the light themselves, which is traced by the cameras.

Some of the earliest motion capture systems utilised a similar idea. The subject was fitted with flashing light bulbs located on anatomical landmarks and recorded using a video camera. Collaboration of each frame allowed the investigator to view the trajectory of a particular landmark (namely hip, knee and ankle) during a gait cycle (Rowe 2013). Active marker systems employ the same idea but the software allows a much more technical analysis. The majority of systems will now also implement infra-red light instead of visible light as it is invisible to the naked eye. Active markers can be useful when measuring over long distances or large capture volumes. This is due to the inverse square law which states that, $E= I/d^2$, where E is the intensity of the light, I is the irradiance and d is the distance from the source, i.e. the active marker (O'Nolan 2013). Therefore, if d increases, a smaller irradiance of light will be needed to produce the same intensity (Ryer 1998). It is this phenomenon which allows capture over a greater distance or volume. However, active makers tend to be more expensive than passive markers and will require a power source such as a battery or even cables attached to the subject. Batteries can add excess weight to the markers and cables may get in the way of the subject performing certain movements, both of which can affect the subject's performance and hence the analysis and results.

When a large capture volume or distance is not required, passive markers are a suitable alternative. These reflect back light which is emitted from the system, near the lens of the camera. For most systems, the threshold of the camera can be adjusted so that only the markers are detected and other artefacts such as skin and clothing are not (Steves 2013). The advantage of these markers is that they are much cheaper than active markers and don't require a power source and are therefore less likely to impinge a subject's movement.

Regardless of what type of system is being used, the process of carrying out a motion analysis session remains similar. Markers are attached to the subject on the area of interest and the system records throughout the required action. Most systems come with

their own software package which allows processing of the session and playback of the recordings. In the majority of cases a data file (often .csv or .txt) will be generated with contains the co-ordinate location of each marker and possible other parameters such as joint flexion/extension angles.

The majority of motion analysis systems, both 2D and 3D, will also allow the option of incorporating forceplate and electromyography (EMG) data. Forceplates can be extremely useful when conducting gait analysis sessions as they allow the user to view the direction and magnitude of the ground reaction force (GRF). An understanding of the magnitude and line of action of GRF with respect to anatomical joint centres and segment centre of mass' can be very useful in diagnosing some types of pathological gait.

The incorporation of EMG data into motion analysis is also incredibly useful. It allows the investigator to monitor muscle activity throughout a desired movement. A number of studies have investigated muscle activation during the gait cycle and many are in agreement about which muscles should be firing at certain stages of the cycle (Whittle 1996; Winters *et al.* 1987). EMG data which doesn't follow this regular pattern could not only be indicative of pathological gait but could also tell the investigator exactly which muscles are causing the problem.

1.3.4 Simi Aktisys

Simi claims to be one of the leading brands in motion analysis software, offering a number of data analysis packages for 2D or 3D motion capture. Aktysis is their 2D data analysis software package.

The manufacturer's website claims that aktysis is the "quickest and most simple way of conducting movement analyses" (Simi 2013[1]). Aktysis utilises coloured LED markers and is capable of calculating gait parameters from recorded video or from live video stream. The software is capable of automatic tracking of LED markers which negates the need for manual digitisation of video frames. The resulting gait analysis report contains data and pictures to better illustrate the results (Figure 2).

[1] http://www.simi.com/en/products/movement-analysis/simi-aktisys-2d3d.html.

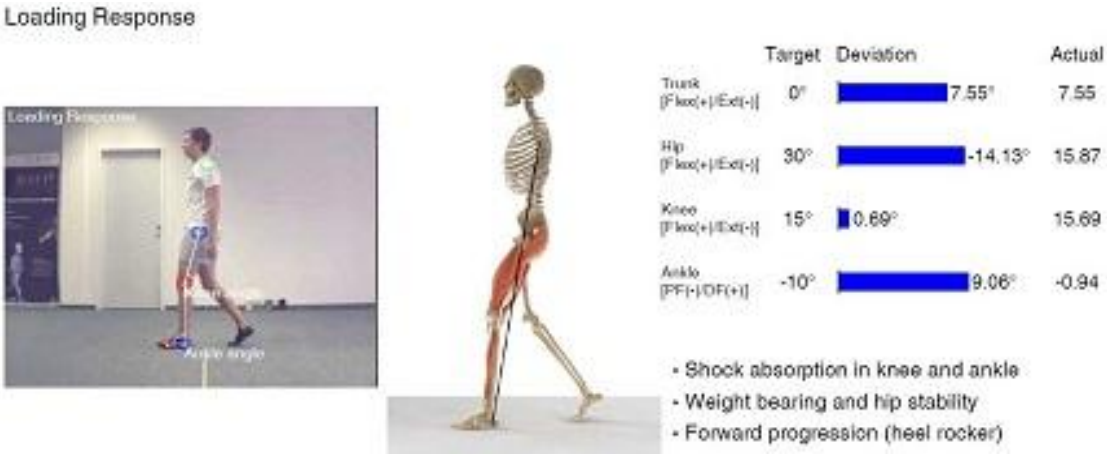

Figure 2. Example of output report from Simi Aktysis 2D motion analysis software (Simi 2013).

In order to be able to use the Simi Aktysis software, the compatible hardware must also be purchased from Simi. The hardware consists of a camera capable of sampling at 100Hz, a tripod and camera cable and 5 LED markers. The newest version of the software (Simi Aktysis 1.3) allows integration with external devices such as forceplates and EMG electrodes to give a more complete output report of the gait analysis session (Simi 2013).

While the Simi Aktysis software may look impressive and claim to be the best in 2D motion analysis, there is a distinct lack of clinical validation regarding these claims. To the author's knowledge no investigation has been conducted to determine the accuracy and precision of Simi Aktysis in comparison to the gold standard in 3D motion analysis. Until its validity has been proven, use of Simi Aktysis software for clinical gait analysis remains questionable. In addition to this even the simplest hardware and software configurations of Simi Aktisys come at a cost of several thousand pounds.

1.3.5 Templo

Contemlplas offers a similar software package to Simi under the name of TEMPLO. TEMPLO software is available in three versions; templo professional, templo basic and templo lite. Templo professional is equipped to deal with multiple camera systems and 3D analysis; however the temple basic software is marketed for use in 2D motion analysis. The manufacturer's website states that this software package is ideal for use in sport, research and the clinic. The software employs the use of retrorelfective markers for automatic tracking during analysis and also compiles the resulting data into an easy to understand report. An advantage of this software package over the Simi Aktysis is that specific

hardware is not required; the software is compatible with any video capture device (MAR 2013; Contemplas 2013). While this may save on expense, it could create problems if a suitable camera is not used. The reviewed literature did not reveal any investigation into the performance of TEMPLO basic with video cameras which sample at different frequencies. It could be the case that the software performs inaccurately when used with a camera which samples at a frame rate lower than 100 or even 50 Hz, which could lead to an inaccurate gait analysis report. The manufacturers are claiming that the software is suitable for clinical use however it seems that some guidance or reassurance on which type of video capture device to use should be provided.

Furthermore, there is a lack of clinical validation of the software's accuracy and precision in comparison to the gold standard in motion analysis. This raises similar issues to those discussed in the previous section regarding the Simi Aktysis software.

1.3.6 Optotrak Certus

One of the most advanced 3D motion capture systems available is the Optotrack Certus© (OC) system. It utilises a motion sensing trinocular camera which is just over 1m long and can be mounted on a caster base for ease of movement. This allows the system to be fully portable. The motion sensing camera is not capable of detecting movement unaided and therefore the use of infra-red emitting diodes (IREDs) as markers is utilised. The markers indicate certain points on the body which the camera is capable of recognising and allows a 3D image of the subject to be created using stored anthropometric data. The complexity of this system allows a number of parameters to be set by the user, including the order in which the markers are strobed and the frame rate of the camera. Motion capture is fast and simple with this system, aided by the fact that the entire system is pre-calibrated which negates the need to recalibrate prior to each session. The manufacturer also states that up to 8 cameras can be used simultaneously, allowing increased capture volume and more accurate marker detection. It also comes with its own software package which allows for fast and simple data processing along with playback of the recorded movements (Northern Digital Inc.). Barnes *et al.* (2008) carried out a bench test of the OC system and reported its accuracy to be within the region of 0.02mm for single marker trajectory. Mazumder *et al.* (2011) tested the percentage error of the OC system in static dynamic and angular movement situations. For static and dynamic trials the percentage error ranged from 0.56-0.57%, which suggests high accuracy. However, percentage error in the angular trials was reported to be approximately 4.012%, which, although still relatively

low, is much higher than that of the static and dynamic trials. Due to the different methodologies used by each study, comparison of the results is not possible. However, the fact that the OC has been bench tested and its accuracy has been proven by separate studies suggests that it is an appropriate system for use in clinical trials, unlike the majority of 2D software packages which have not been validated.

Despite being a 3D motion capture system, the OC is marketed for use with only one trinocular camera. This could have an effect on parameters such as depth perception which could have a knock-on effect to results, thus making them less accurate. The manufacturer's website states that multiple camera configurations can be used and up to 8 motion sensing cameras can be used simultaneously (Northern Digital Inc 2013). This could be a useful way to combat the problem of a single camera but will incur a considerable increase in cost. It would also subtract form the portability of the system, so the user would need to decide if portability or use of a multiple camera system is paramount to their needs.

1.3.7 Vicon T-Series

Vicon has been well established as the gold standard in 3D motion capture and analysis. The T-series boasts the highest resolution of any motion capture camera commercially available at up to 16 megapixels. The Vicon T-series cameras are also capable of capturing at up to 120 frames per second (fps) (Vicon 2013). There are a few major differences between the OC and Vicon. Vicon utilises passive markers instead of active IREDs and infra-red light is strobed from the cameras rather than the markers themselves. Vicon is also less portable than the OC, however it does allow a higher number of cameras to be used simultaneously and therefore capture volume is not compromised. Vicon also comes with its own software package, Nexus. Nexus allows for detailed processing of sessions, along with playback of movements and export of comprehensive numerical data files that fully characterise the 3D motion of the gait analysis participant.

Ehara *et al.* (2005) reported the accuracy of a number of 3D camera systems. It was stated that the mean error of the Vicon system was 2.3mm. In comparison to the other systems tested, the Vicon was amongst the most accurate. The accuracy of Vicon can be further validated by its use in several studies to bench test new motion capture devices (Barker *et al.* 2005; Godwin *et al.* 2009).

1.4 Uses of Motion Capture

1.4.1 Sports

Motion analysis has been widely used in a variety of professional sporting activities to improve technique and aid in injury prevention. One area of focus within the professional sporting community is golf swing analysis. There are a number of investigators who have used fully instrumented 3D motion analysis systems to analyse the swing of professional golf players (Healy *et al.* 2008; Murakami and Mochimaru 2010). Both Healy and Murakami used 3D Vicon camera systems to track the movement of players in 3D space accompanied with force plate data to fully analyse the swing pattern of a number of golf players.

Dun *et al.* (2008) investigated the kinematic differences between pitching a particular baseball throw at different stages of the throwing cycle. They hypothesised that there would be significant changes in kinematic position at front foot contact for each of the variations. The investigation utilised both a 6 camera and an 8 camera 3D motion capture system which used retro reflective markers.

Hreljac (1997) investigated the response of individuals to differences in tennis shoe midsole hardness. The study utilised Kistler force plates and a high speed camera from which kinematic data would be collected. Results showed that individuals do respond differently to shoes with different midsoles hardness. This study highlights the use of 2D motion analysis and validates its ability to detect subtle kinematic changes.

Not only is motion analysis widely used in the sporting community to evaluate performance, it is also used to understand the mechanisms of injury and therefore aid in injury prevention. In a review article Bahr and Krosshaug (2005) stated that a description of whole body and joint biomechanics at the time of injury could potentially increase understanding of injury mechanisms and how to prevent injury. They focus on load and load tolerance being a major contributor to sports injuries, therefore, analysis of loads such as ground reaction force (GRF) using motion analysis software could aid in the understanding and prevention of sporting injuries.

1.4.2 Clinical

Although motion analysis can be used across a wide variety of disciplines, one of its most common uses and one of the primary drivers for the science's original invention is

within the clinical setting. A number of clinicians use a variety of motion analysis techniques, from visual methods to fully instrumented 3D analysis, in order to quantify positive changes in patients following treatment and to compare treatment types. For example, Kitaoka *et al.* (1994) used 3D motion analysis to determine the effectiveness of non-operative treatment of intra-articular fractures of the calcaneus. Patients were treated with casting rather than surgery and their gait was analysed approximately 6 years following treatment to determine the presence of any residual functional deficit. Platz *et al.* (2001) used 3D motion analysis to determine if there was a deficit in aimed movements of the arm in hemiplegic stroke patients when compared to healthy controls. They also investigated whether structured training of the affected arm would lead to any significant changes in the movement analysis results. They found that even when baseline performance of stroke sufferers was high, skilfulness could still be improved by use of a structured training program. It is out with the scope of this thesis to document the long and varied history of the application of motion analysis in the clinical environment. Both of the investigations cited above highlight the usefulness of motion analysis when assessing patient improvements following treatment or comparing treatment types, and some additional examples of previous work are offered in the following sections.

1.5 Clinical Relevance of Motion Capture

Within the clinical setting there are a number of disciplines to which motion analysis can be applied. Some of the more common treatments which incorporate motion analysis include cerebral palsy (CP), stroke and amputee rehabilitation. A compromised gait due to muscle spasticity is a common symptom of CP. Gait analysis can often help to diagnose the cause of pathological gait and therefore aid clinicians in developing an appropriate treatment plan.

It has been shown that gait analysis can drastically alter the treatment plan for CP patients. A number of studies have investigated this effect. Cook *et al.* (2003) compared treatment recommendations for CP patients before and after 3D gait analysis. Results showed an overall reduction in the number of patients who were recommended for surgery. In a similar study by Lofterod *et al.* (2007) it was stated that after 3D gait analysis 42 of the 60 patients tested had their treatment plan altered. Furthermore, the number of surgical procedures recommended for CP children was reduced by 13%. DeLuca *et al.* (1997) also stated that gait analysis changed surgical recommendations in 52% of patients

tested. The reduction in numbers of patients recommended for surgery is a key element to clinical gait analysis. Not only does this save respective health services substantial costs, but it also reduces patient trauma from undergoing unnecessary surgery.

Although the aforementioned investigations were successful in reducing the number of patient surgeries and ensuring the correct treatment plans, all used fully instrumented 3D motion capture systems. While this may achieve reliable and desired results, it is impractical for the widespread use of clinical gait analysis for a number of reasons. Skaggs *et al.* (2000) reported that while gait analysis itself is objective, there can be some subjectivity in the interpretation of the data. The level of subjectivity in data interpretation is likely to decrease the more experienced the investigator is, however this then limits the use of advanced systems to those with technical expertise. It would be unreasonable to expect that all clinicians who are required to conduct gait analysis sessions will possess this level of technical proficiency, and many clinical sites do not have the resources to employ a dedicated clinical scientist, technician or bioengineer. As well as data being difficult to interpret, 3D gait analysis laboratories are expensive with a top of the range 12 camera system costing up to £500,000 to purchase and a further £200,000 a year to run (Rowe 2013). The combination of these factors makes fully instrumented 3D gait analysis in the widespread clinical setting both technically and financially inaccessible.

1.6 Clinical 2D Motion Capture

It would seem logical that a reasonable alternative to fully instrumented 3D analysis would be the much cheaper 2D analysis. However, it appears that there is a distinct lack of clinical 2D motion analysis, with most clinicians opting for visual assessment when 3D analysis is unavailable. It may be that clinicians are opting for visual rather than 2D analysis because they feel that 2D analysis will not reveal clinically relevant movements in other planes beside the sagittal and coronal. However, there is substantial evidence that the majority of gait deviations in children with CP occur in the sagittal plane. Winters *et al.* (1987) analysed gait patterns in children with spastic diplegic CP and separated them into 4 groups depending on the severity of their gait deviations. In every group the main deviations were limited or hyper flexion/extension of lower limb joints, all of which can be accurately measured or at least appropriately approximated in the sagittal plane. Wren *et al.* (2005) stated that common gait abnormalities in children with CP included stiff knee and increased hip flexion, both of which can also be measured in the sagittal plane. It was also

stated that in-toeing and hip adduction were common, and whilst these cannot be measured in the sagittal plane, video recording can also be taken in the coronal and transverse planes for 2D analysis. Finally, Sutherland and Davids (1993) stated that most common abnormalities of the knee in children with CP occur in the sagittal plane. From this evidence it seems that 2D analysis would often be a suitable tool to detect many gait abnormalities in CP patients, and also to provide a patient referral pathway where more comprehensive fully instrumented 3D assessment is indicated.

There is also substantial evidence that visual assessment of gait is not an appropriate substitute for instrumented 3D analysis. The EVGS was earlier discussed and has been proven to be a reliable visual assessment tool for gait analysis in CP children. However, when compared directly to 3D analysis, the EVGS seems to fall short. Kawamura *et al.* (2007) compared the EVGS to 3D gait analysis and found that the majority of visual observations were not reliable and a strong disagreement was found between observational gait analysis and 3D gait analysis. The importance of technical expertise is again highlighted in the use of visual assessment tools in an investigation by Ong *et al.* (2008). In Ong et al. (2008) the accuracy of the EVGS on inexperienced observers was tested and it was found that results were less accurate when compared to those of experienced observers. However, this is true of almost all subjectively employed assessment tools and it may be suggested that with training and appropriate experience, visual gait scoring systems could be valuable additions to clinical gait laboratories' repertoires.

The reviewed literature revealed a distinct lack of investigations which utilised 2D motion capture systems or software analysis to detect clinically relevant deviations from normal kinematics. This could be due to the lack of validation studies regarding 2D motion capture systems.

1.7 Literature Review of 2D and 3D Comparison Studies

The limited use of clinical 2D analysis is likely to be due to its lack of formal validation. There are a limited number of investigations which have studied the performance of 2D systems in comparison with 3D. Furthermore, those studies which have undergone comparisons tend to focus on very specific movements which makes the validation of 2D analysis for the general measurement of the gait cycle limited.

Cornwall and McPhoil (1995) compared the results of motion analysis with 2D and 3D systems on rear foot motion during walking. A comparison of 2D and 3D analysis of foot

inversion and eversion during walking was investigated to determine if there were any significant differences between the methods. Two dimensional recording was carried out with a super VHS camcorder placed 5 metres behind the subject, perpendicular to the plane of desired motion. The video recorded at 60 fields per second, and subsequent analysis was performed using the Peak Performance 2D automated analysis software. Three dimensional recording utilised 3 cameras positioned along the right hand side of the walkway and subsequent analysis was performed using the same software package as was used for 2D analysis.

Results showed no significant differences between measurement methods between 8 and 60% of the stance phase. The authors concluded that 2D analysis can be utilised clinically to assess rear foot motion during walking. However, limitations include the restricted duration of the stance phase during which the two measurement methods were in agreement and also the fact that no subjects with pathological gait were tested. Further study should be conducted to determine the ability of 2D analysis to detect rear foot motion pathologies to the same extent as 3D analysis.

Nielsen and Daugaard (2008) carried out a comparison of angular measurements during gait by 2D and 3D measurement systems. The aim was to validate the use of Hu-m-an digitising software for clinical use. Participants were subjected to simultaneous capture with sagittal plane video recording and 3D recording. Parameters under investigation included knee and ankle angles. Results were analysed during the whole gait cycle, at initial contact (IC), during stance phase and during swing phase.

Results showed significant differences for the ankle at all stages and for the knee during swing and at IC. However, there was no significant difference for knee angles at stance. Despite these differences, intra-class correlations were high for both the knee and ankle during swing. It was concluded that Hu-m-an digitising software could not be validated from the study alone and further validation would be required.

1.8 Introduction to Visualisation of Human Movement (VOHM)

VOHM is a bespoke software utility which may be used to capture video data from digital video cameras and process in (close to) real time, or offline, the image sequences in order to automatically identify and track the motion of anatomical points of interest (Murphy *et al.* 2011; Murphy *et al.* 2012). In its current form the system primarily supports video acquisition via the Gig-E vision standard at up to 230Hz (though 50-100Hz is

suggested for conducting analysis of human gait). In order to calculate a participant's shank to vertical angle, thigh to vertical angle, and knee flexion angle (the kinematics under consideration ion the current study) a marker set is required which consists of 3 small green paper markers attached to the participant at appropriate palpated anatomical landmarks. By exploiting similar techniques to the common "green screen" used in commercial environments VOHM automatically identifies the paper markers and tracks their motion during walking trials; this then permits calculation of the relevant kinematic parameters over the familiar time course of acquired gait cycles (Murphy *et al.* 2011).

VOHM functionality also permits video processing, batch processing, event detection, gap filling, data export and incorporation of analogue signals such as GRF; all of which is controlled from a simple striped back bespoke graphical user interface (GUI) shown in figure 3.

Setup Default thresholds Process video

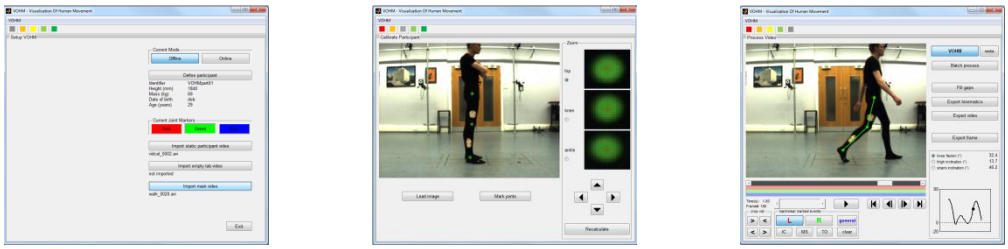

Figure 3. Screenshots of the VOHM GUI. Setup allows definition of participants and session settings; default thresholds determine RGB thresholds for marker tracking; process video incorporates a bespoke media player and automatically detects and tracks joint markers. All functionality is via pushbuttons and ribbons; additional panels not shown here permit integration of additional hardware such as forceplates.

1.9 Aims

This study aims to establish the concurrent validity of a gold standard 3D motion analysis system with the VOHM 2D motion analysis system. Parameters under investigation will include shank inclination angle (SHANK) thigh inclination angle (THIGH) and knee joint centre flexion/extension angle (KJC).

2. Methodology

2.1 Participants

This investigation was approved by the departmental ethics committee at the Department of Biomedical Engineering, University of Strathclyde. Ten participants (5 male; 5 female) volunteered for this investigation which took place in the Biomechanics Lab in the

Department of Biomedical Engineering at the University of Strathclyde. All participants were healthy, able-bodied adults between the age of 18 and 30. Inclusion criteria required participants to be able to walk at a self-determined pace without excess physical exertion or pain. Participants were required to read, understand and sign a participant information sheet prior to taking part in the study (appendix I). Participants' age and anthropometric data is sown in table 1.

Table 1.

Height (cm)	Mass (kg)	Leg Length (cm)	Ankle Width (cm)	Knee Width (cm)	Inter ASIS distance (cm)	Age (years)
174.6 (9.8)	76 (15.5)	92.1 (7.7)	6.7 (0.7)	10.6 (0.9)	24.9 (1.9)	23.3 (2.8)

Participants' anthropometric data and age displayed as mean (S.D).

2.2 Hardware and Configuration

3D analysis was carried out using a 12 camera Vicon T-series motion capture system sampling at 100Hz. Prior to each session the cameras were calibrated to within 0.5 mm. Data was collected using Vicon Nexus software. A Basler Ace series video camera which also sampled at 100Hz was used to capture video for 2D analysis. The camera was set-up to record participants in the sagittal plane and was placed 3m from the walkway. Camera zoom was adjusted so that the region of interest (foot contact to foot contact of the right leg) was in the centre of the capture area. Prior to each session the aperture, focus, white balance and gain were adjusted to provide optimal footage.

2.3 Testing Protocol

Participants were asked to wear tight fitting black shorts or leggings. Male participants were topless while female participants were asked to wear a short top which allowed the pelvis to be exposed for marker placement. Prior to testing anthropometric data was collected from each participant. Height (cm) was measured using a stadiometer accurate to within 0.25cm; weight (N) was measured using Kistler forceplates and mass (kg) was calculated by dividing weight by 9.81 (acceleration due the earth's gravitation field). Leg length was measured from the anterior superior iliac spine (ASIS) of the right leg to the inferior medial malleolar notch. Knee width, ankle width and inter ASIS distance were measured using a pair of callipers which were accurate to within 1 mm. Knee width was defined as the distance between the medial and lateral femoral epicondyles and ankle width was defined as the distance between the medial and lateral malleoli.

Following anthropometric measurements, retroreflective markers were attached to participants' right leg using a bespoke marker arrangement (Papi 2012). Markers were attached to the following anatomical landmarks: right and left ASIS; right and left posterior superior iliac spine (PSIS); distal aspect of the first and fifth metatarsal heads and the calcaneus at a vertical height matched to that of the metatarsal markers during bare flat foot standing. Static calibration markers were also attached to the medial and lateral femoral epicondyles and the medial and lateral malleoli. Cluster marker sets consisting of four markers were placed on the thigh and shank and secured using elastic straps and micropore tape. Where possible cluster markers were placed on areas of low muscle mass to avoid movement of the clusters during walking form muscle contraction (Davis *et al.* 1991). Retroreflective marker placement is shown in figure 4. Following marker attachment, approximately 200 frames were captured with Vicon of the participant standing in a static position within the capture volume and calibration markers were then removed.

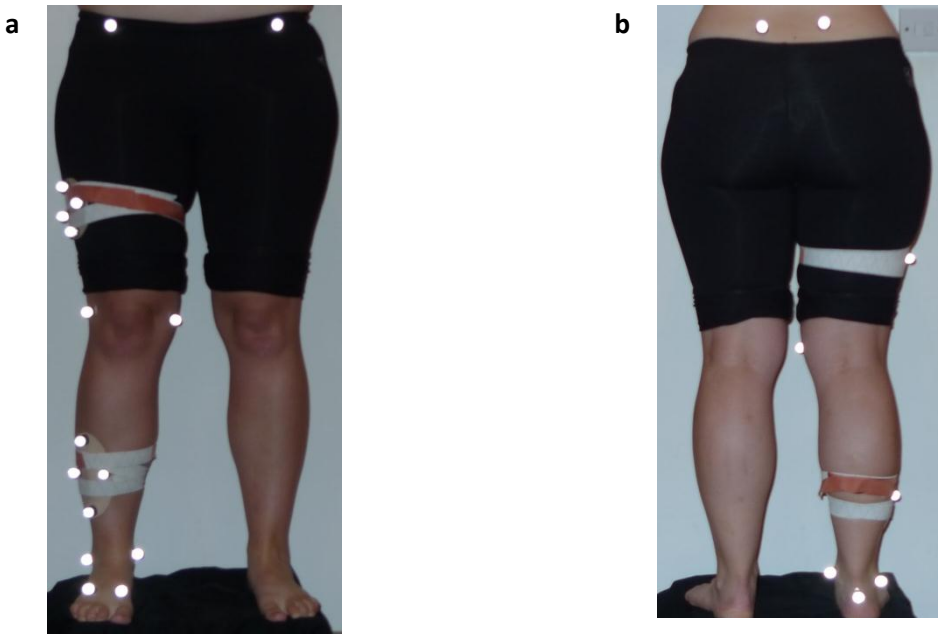

Figure 4. Retrorelfective marker placement. **a.** Anterior **b.** Posterior.

VOHM utilised circular green paper markers, approximately 4cm in diameter. VOHM markers were attached after the removal of the retroreflective calibration markers at the following anatomical landmarks: the greater trochanter of the femur; the lateral femoral epicondyle and the lateral malleolus. VOHM marker placement is shown in figure

5. Ten frames were captured using the video camera of the participant standing in the middle of the capture area with the right side facing the camera and the arms folded across the chest for calibration purposes.

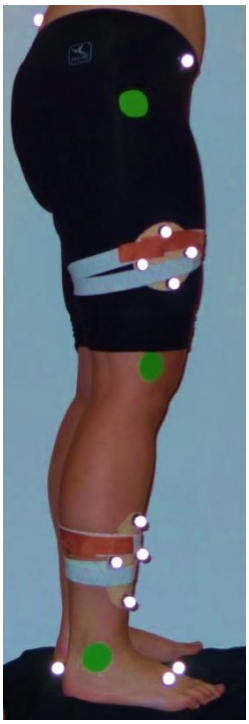

Figure 5. VOHM marker placement, sagittal plane.

Participants were then asked to perform a couple of practice walks before any data was captured. They were requested to look up towards a mark on the wall in front of them to avoid forceplate targeting and walk at a self-selected pace with their arms swinging. Practice walks were carried out until the participant was comfortable and there was a clean strike on the laboratory forceplate with the right foot (as visually assessed by the investigator in real-time). During walking trials data was acquired simoltaneoulsy from VOHM and Vicon. Walking trials continued until a minimum of 5 successful trials had been obtained. In order for a trial to be considered successful, the video must have captured initial and subsequent foot contact of the right leg and there must have been a clean strike on the laboratory forceplate.

2.4 Data Processing

2.4.1 VOHM

Participant videos were cropped to the region of interest. The user identified the frame of initial foot contact and the frame of subsequent foot contact for the right leg for all trials. These frames were logged and videos were cropped using Matlab. Once cropped the videos were processed using VOHM; note that VOHM incoprporates a video cropping feature, but as many walking trials were conducted for several participants in this study a custom script was written to reduce computational time for a large batch process. For each participant, the static calibration video was imported and marker identification was performed by the investigator. A batch process allowed automatic processing of all participant trials. The data output from VOHM consisted of a video file with automatic marker detection overlay and an excel file containing the following data: x, y and z coordinate data for the hip joint centre, knee joint centre and ankle joint centre; shank inclination angle (SHANK); thigh inclination angle (THIGH) and knee joint centre flexion/extension angle (KJC).

2.4.2 Vicon

Vicon trials were cropped using Nexus to only include the region of interest. Initial foot contact was defined by the first appearance of the GRF. Subsequent foot contact was defined by tracing the height of the heel marker. The height at which initial foot contact occurred was recorded and used to identify the point at which subsequent foot contact occurred. Due to the use of a bespoke marker arrangement, a customised virtual skeleton template (VST) was created using Nexus. Vicon trials were then processed allowing the output of an excel file containing the following data: shank inclination angle; thigh inclination angle and KJC flexion/extension angle.

2.5 Data Analysis

Following processing Vicon data and VOHM data for all participants and all trials was stacked and normalised to 100% gait cycle using a simple linear regression fit in Matlab. Whilst VOHM is capable of performing gap filling via piecewise cubic spline interpolation; it was found that participant 1 exhibited almost no arm swing during walking, thus the greater trochanter marker was permanently occluded from the digital video camera. Therefore, results from participant 1 were excluded from analysis due to lack of THIGH and KJC data from VOHM. Data processing was performed using SPSS and Microsoft

Excel. Comparisons were made using a database of all 83 recorded gait cycles and data was subject to appropriate statistical modelling.

3. Results

Descriptive statistics from every trial for SHANK, THIGH and KJC are shown in table 2.

Table 2.

Parameter	Mean	Std. Deviation (S.D)
Vicon SHANK	17.2	22.4
VOHM SHANK	15.4	22.4
Vicon THIGH	-6.2	15.1
VOHM THIGH	-8.4	14.5
Vicon KJC	23.7	21.8
VOHM KJC	23.4	19.5

Descriptive statistics for all parameters from VOHM and Vicon data

Figure 6 shows graphical representation of the variation in means for all trials. Figures 6a, b and c show that there was little variation in the means for data collected with VOHM compared to Vicon.

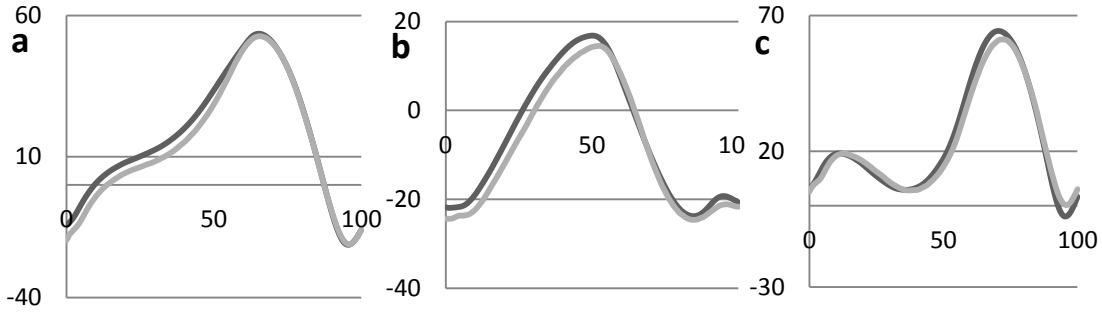

Figure 6. For all graphs dark grey represents vicon data and light grey represents VOHM data. X axis - trial number, Y axis - Degrees. **a.** SHANK. **b.** THIGH. **c.** KJC.

Table 3 describes the spearman's rho (ρ) and intra class correlations (ICC) for each parameter. The spearman's ρ correlations for SHANK, THIGH and KJC showed significant agreement ($P<0.001$) with values of 0.99, 0.93 and 0.94 respectively. The ICC values for SHANK, THIGH and KJC also showed significant agreement ($P<0.001$) with values of 0.99, 0.96 and 0.96 respectively.

Table 3.

Parameter	Spearman's ρ	ICC
SHANK	0.99	0.99
THIGH	0.93	0.96
KJC	0.94	0.96

Spearman's Rho (ρ) and ICC for SHANK, THIGH AND KJC. α=0.01.

Linear regression analysis was performed on VOHM data against Vicon data, model design required no constant "y" offset to be included so that VOHM was the only predictor of Vicon. Residuals were found to be normally distributed. Table 4 shows the R^2 and B values for each parameter. The R^2 values showed a significant correlation (P<0.001) between the two systems for each parameter. The values of R^2 for SHANK, THIGH and KJC were 0.98, 0.96 and 0.97 respectively. The mean residual values for each parameter were all relatively low which indicates small deviations from the regression line in all cases. The B value for SHANK was 1.04, indicating that VOHM may systematically underestimate SHANK in comparison to Vicon. The B value for KJC was 1.05 which also indicates an underestimation of this parameter by VOHM. However, the B value for THIGH was 0.93 which indicates that VOHM tends to overestimate THIGH in comparison to Vicon.

Table 4.

Parameter	R^2	Mean Residual	B
SHANK	0.98	1.9	1.04
THIGH	0.96	1.6	0.93
KJC	0.97	-0.7	1.05

R^2, mean residual and B values from regression analysis of VOHM data against Vicon.

Figure 7 shows regression analysis charts for each parameter. All charts show a limited spread of data from the regression line, with SHANK displaying the smallest spread. There are no obvious outliers or extraneous data points in figure 7a, b or c.

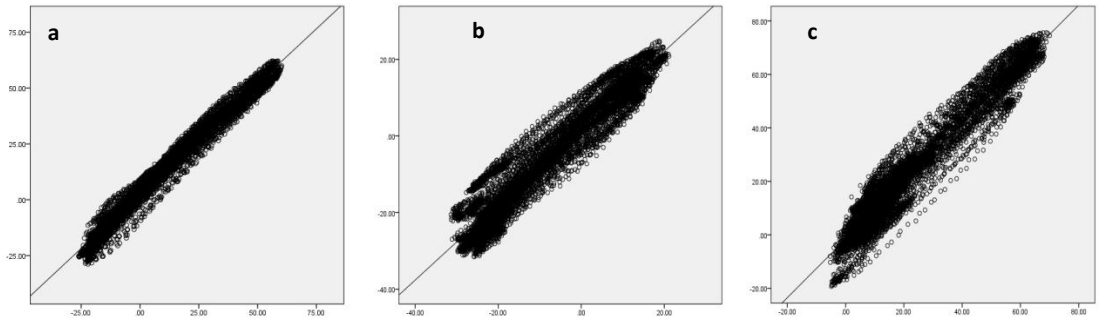

Figure 7. Regression charts for VOHM data against vicon data. X axis – VOHM data, Y axis – Vicon data. **a**. SHANK **b**. THIGH **c.** KJC.

Bland-Altman plots are a useful statistical tool for comparing two measurement methods. Data is displayed as points within a high locus of agreement (LOA) and a low LOA which are calculated by adding or subtracting 2 standard deviations (S.Ds) respectively from the mean difference between the two measurement systems. If data points lie within the high and low LOA then there is said to be good agreement between the two measurement methods (Bland and Altman 1986). For each of the parameters, the Bland-Altman plots revealed high levels of agreement between the two measurement methods. These are shown in figure 8.

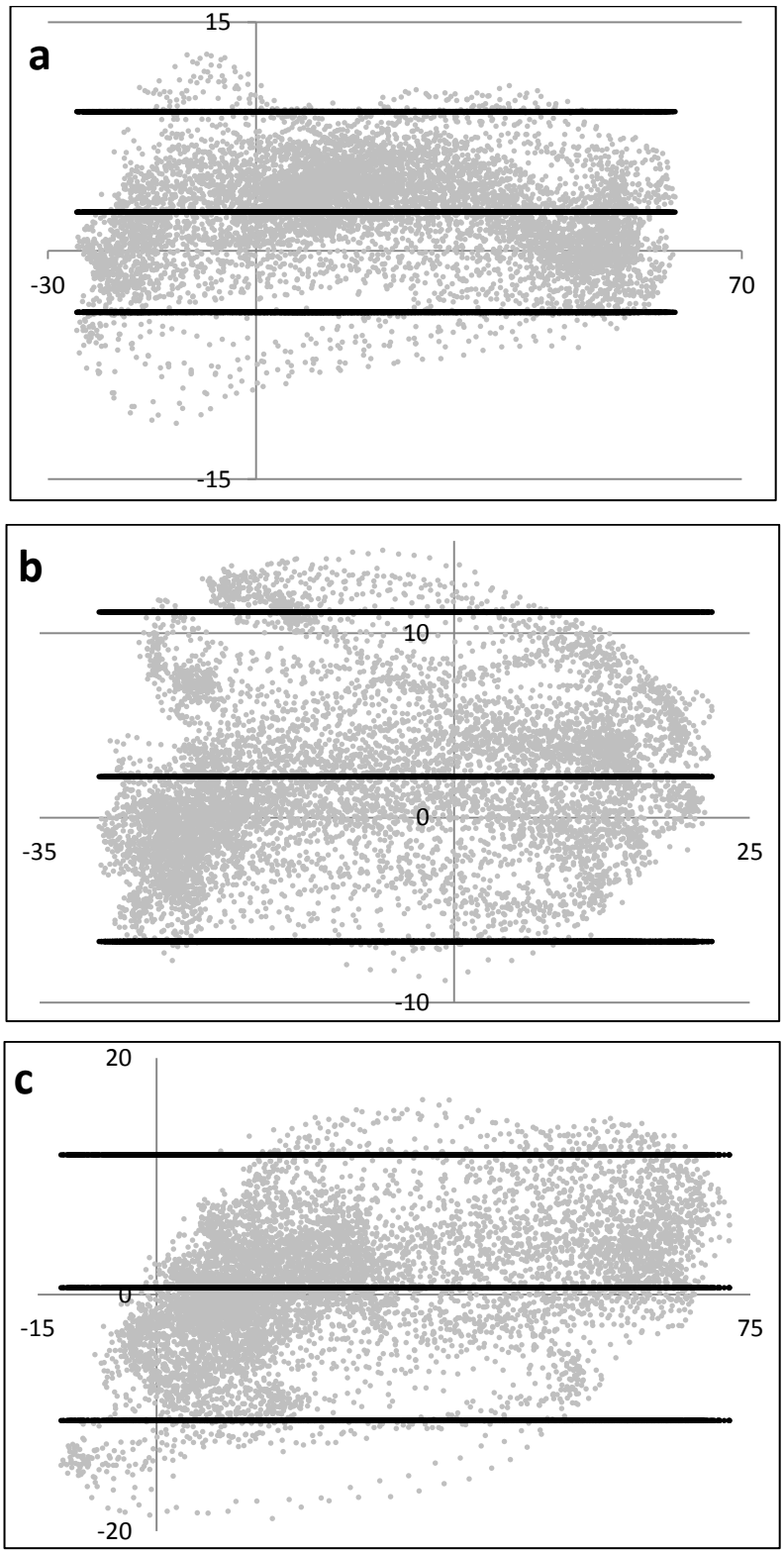

Figure 8. Bland-Altman plots for all parameters. X axis - Mean value of all Vicon and Vohm data for parameter of interest, Y axis - Difference between Vicon and VOHM value for parameter of interest. Top solid line – High LOA. Bottom solid line low LOA. Middle solid line – mean difference between Vicon and VOHM data. **a.** SHANK **b.** THIGH **c.** KJC.

For SHANK the percentage of data points within the LOA was 94.9%. Similarly, for THIGH the percentage of data points within the LOA was 94.5% and finally for KJC the percentage of data points within the LOA was 94.3%.

4. Discussion

This study aimed to validate a bespoke piece of 2D motion analysis software to the gold standard in 3D motion analysis for its potential use in clinical gait analysis.

While results were promising and showed excellent agreement between the two systems, there were a number of limitations with this study. Ethical approval required that only able bodied participants be tested initially. If VOHM were to be used clinically then its validation would need to stand up to use with patients who may possess severe gait abnormalities. Although it makes sense to carry out an initial bench test with able bodied participants, further validation with individuals who suffer from gait abnormalities would only increase the validity of VOHM for use in the clinic.

Limitations also existed within the testing protocol. Firstly, palpation of anatomical landmarks for marker placement can be subjective in some cases, depending on the build of the participant. In difficult cases landmarks were palpated by multiple investigators to try and reduce error due to incorrect landmark identification. There is also the issue of marker movement during gait due to soft tissue artefacts. Capozzo (1991) investigated the effects of soft tissue artefacts on marker location and found that the most affected angle was internal rotation of the joints of the lower limb (hip, knee and ankle). However, the deviations were only ±1°. This suggests that errors in the data were unlikely to be due to marker movement.

During data processing the user was required to manually crop all VOHM and Vicon trials from initial foot contact to subsequent foot contact on the right leg. This was a subjective process as the user had to manually identify the frame at which contact occurred. Subjectivity was minimised by defining a method by which foot contact would be identified with both VOHM and Vicon and this was adhered to for all trials. However, it is possible that trial lengths for VOHM and Vicon data may not marry up perfectly for all trials. This could be another source of possible error between the systems. However to determine whether or not this is the case, data from the start and end of the gait cycle

would need to be examined separately to determine if there was a higher rate of error than, for example, at mid-stance. The subjectivity regarding the point of foot contact could have been avoided by the use of footswitches which inform the user of the exact moment of foot contact. However, footswitches require participants to be shod so the testing protocol would need to be amended from participants walking barefoot to participants walking shod.

In general, one of the issues which can arise when using 2D gait analysis is the use of single plane recording. This limits the ability of the system to detect markers if they are obscured in the plane of video capture. For example, participant 1's data was excluded from analysis due to inadequate arm swing causing continual occlusion of the hip marker. This left too many gaps in the data for THIGH and KJC and comparison of trials between VOHM and Vicon was not possible. Unfortunately, this is one of the drawbacks of 2D analysis. It would be inappropriate to request that a patient or participant incorporate a larger arm swing into their walk as this would cause them to deviate from their normal walking pattern and therefore not give the most reliable results. This drawback could be overcome by further developing the software to detect a smaller area of marker, or attempting to change the location of marker placement to better avoid the arm swing.

When comparing data from 2D and 3D measurement systems there are likely to be slight differences in the values obtained. This is mostly due to movements of the lower limb during the gait cycle such as internal and external rotation of joints which 2D systems are unable to detect. Capozzo (1991) compared 2D and 3D reconstruction of gait data. It was reported that the maximum difference in hip flexion angle was approximately 10°, the maximum difference in knee flexion angle was <5° and the maximum difference in ankle flexion was >10°, suggesting that the hip and ankle angles suffered the most from 2D approximation. Depending on the intended application of the results, a deviation of 10° between systems could be considered significant. The reviewed literature did not reveal what should be considered as significant differences between 2D and 3D gait data.

When mean values from VOHM and Vicon were compared for each parameter the average difference in SHANK and THIGH was approximately 2° and the average difference for KJC was <1°. These results are in agreement with Capozzo in that the KJC showed the

smallest difference, however the values for the differences between systems are much smaller. McGinley *et al.* (2009) investigated the reliability of 3D kinematic gait measurements and suggested that an error of 2° or less is likely to be considered acceptable. It was even suggested that errors between 2° and 5° were likely to be reasonable, however they may require consideration on data interpretation. It may also depend on what stage of the gait cycle these errors are occurring. It could be that errors are more prevalent at the beginning and end of data capture, when the subject is at the edge of the capture volume. If this is the case then it is likely they can be easily rectified by increasing the capture volume or beginning capture only once the subject is fully within the capture volume. However, if the errors are occurring at important stages of the gait cycle such as initial foot contact or toe-off then they pose a more serious risk to the results and the validity of the system should be questioned. However, since the errors reported in this study are well within what McGinley reports as 'acceptable' values, the source of the errors are unlikely to require investigation.

Comparison of S.D values showed that for all parameters VOHM displayed the same, if not less, variation than Vicon data. Ehara *et al.* (1995) investigated the S.D of mm error of a number of commercially available motion capture systems which have been recommended for clinical use. Vicon was reported to have one of the lowest S.D values in comparison to other leading brands. Richards (1999) also reported Vicon to have a low range in error value for angular measurements. Since Vicon has been widely validated for clinical use and displays low error values for both position and angular measurements, the fact that VOHM showed lower S.D values than Vicon shows that variation of VOHM data lies within acceptable limits.

Initial analysis of the data revealed a non-parametric distribution which prompted the use of the Spearman's ρ test to determine levels of agreement between data sets. For each parameter the Spearman's ρ value was very high, indicating strong significant agreement ($P<0.001$) between VOHM and Vicon data. Further tests in the form of ICC and Bland-Altman plots were also performed.

The ICC for each parameter also showed significant agreement ($P<0.001$) with values ranging from 0.96 to 0.99. Mean residual values were low, indicating only small

deviations from the regression lines. However, the ICC value and regression chart alone cannot justify a high correlation between measurement methods. High agreement suggest that the majority of data points lie along the regression line, however, there will be high agreement if the data points lie along any straight line. The regression line doesn't demonstrate agreement between the data points, only the strength of the relation between them (Bland and Altman 1983). The agreement between the data points can be determined by examining the B value. For SHANK, THIGH and KJC the B values were 1.04, 0.93 and 1.05 respectively. The largest deviation from 1 across all the B values was 0.07 suggesting that for the majority of data points VOHM and Vicon were in strong agreement. The B values also indicated that VOHM tended to underestimate the value of SHANK and overestimate the value of THIGH. This would mean that the KJC angle would seem bigger. This is reflected in the fact that VOHM also tended to overestimate KJC.

Bland-Altman plots are a useful statistical tool specifically designed to compare two scientific measurement methods. The number of points which lie within the LOA indicates the level of agreement between the measurement methods. Currently, analysis of Bland-Altman charts relies on visual interpretation only. This makes results obtained qualitative, however, by calculating the percentage of data points which lie within the LOA, results can begin to be interpreted in a quantitative fashion. For SHANK, THIGH and KJC the number of data points which were within the LOA were all over 94%. This suggests extremely good agreement between the two measurement methods. Visual interpretation of the charts also confirms that there are no obvious outliers or extraneous data points.

Cornwall and McPhoil (1995) investigated a comparison of 2D and 3D motion capture of rearfoot motion during walking. While the current investigation cannot be compared directly to Cornwall due to the measurement of different movements, the results obtained are in relative agreement. Cornwall stated that there were no significant differences between the two measurement methods. However, this only applied to between 8 and 60% of stance. Since disagreement is occurring at the beginning and end of the gait cycle, it could be concluded that the capture volume wasn't big enough and the camera used for 2D analysis wasn't obtaining a clear view of the whole gait cycle. Other reasons could include that the parameters which were under investigation (foot eversion and inversion) occurred to a higher degree at the beginning and end of the gait cycle, and

since these movements occur in the transverse plane, the 2D system was unable to detect them as well as the 3D system. Despite these limitations, Cornwall stated that 2D analysis could be utilised to clinically assess rearfoot motion during walking.

Nielsen and Daugaard (2008) also compared 2D and 3D measurement systems; however, they investigated joint angles during human gait. In a similar fashion to this study, participants were subject to simultaneous recording with 2D and 3D systems with knee and ankle angles being the parameters under investigation. Nielsen analysed results for the whole gait cycle, at initial contact, during stance phase and during swing phase. This type of analysis is useful to determine specific points at which errors are occurring and to ensure the 2D system is capable of providing accurate results at the clinically important stages of the cycle. This type of analysis was not carried out in the current investigation due to time constraints but is advised for any future work which is undertaken.

Results from Nielsen showed there were in fact significant differences for both parameters; however the knee showed higher agreement than the ankle. The spearman correlation coefficient was calculated for each parameter at IC and during stance phase and swing phase. The values for the knee ranged from 0.81-0.96 ($p<0.05$) and for the ankle ranged from 0.56-0.81 ($p<0.05$). Comparison of correlation values from the current investigation and Nielsen show that a stronger correlation was found between VOHM and 3D than Hu-m-an and 3D. This could be for a number of reasons. Hu-m-am digitising software required manual digitisation of gait videos which is a subjective and time consuming process and could have led to errors. It is also possible that different data analysis methods contributed to the difference. In Nielsen's study, a random frame was selected from each trial for comparison of angles during the whole gait cycle. Frames were then split into groups depending on whether they occurred during stance or swing phase. The frame at which IC occurred was also recorded for each trial. Angles from each frame were then compared with 3D data. It is likely that this method left fewer trials for comparison than the methos used in the current investigation. The small number of trials for comparison could have contributed to the lower correlation values seen in Nielsen's study.

Based on the results of this bench test VOHM can be recommended for use in clinical gait analysis. Currently, fully instrumented 3D gait analysis is the gold standard tool

for diagnosis and treatment prescription of patients with movement pathologies. However, this is inaccessible to number of patient populations. It seems that a number of clinicians are opting for visual analysis as an alternative, and while a number of visual scoring systems have been validated, the results are not quantitative and rely on technical expertise. 2D analysis seems like an appropriate alternative to bypass the expense and expertise required for 3D analysis. VOHM is the ideal candidate to fill this void as it is one of the only 2D systems which has been validated against fully instrumented 3D analysis. It allows automated, quantitative analysis of human gait without the need for technical expertise or time consuming manual digitisation. The combination of technical accuracy, ease of use and speed of data processing makes VOHM the ideal alternative to costly 3D analysis.

Statistical analyses revealed excellent agreement between Vicon and VOHM for analysing human gait. As a result, VOHM can be recommended for use in the clinic providing that only the parameters under investigation in this study are considered. Further validation of VOHM with more parameters such as ankle and hip angles is suggested. Validation of VOHM with participants who possess gait abnormalities should also be considered.

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Appendix I

Participant Information Sheet

Name of department: Department of Biomedical Engineering
Title of the study: Comparison of a novel 2D motion analysis system to the gold standard in 3D motion analysis

Introduction
The chief investigator for this study is Professor Philip Rowe.

The researchers conducting this study are Dr Andrew Murphy, andrew.j.murphy@strath.ac.uk; 0141 548 2855 and Lindsay Clarke, gtb12170@uni.strath.ac.uk; 07557402054. Andrew Murphy is a Research Fellow within the Department of Biomedical Engineering and Lindsay Clarke is a post-graduate student undertaking an MSc in Biomedical Engineering.

What is the purpose of this investigation?
Analysis of the way the people move and walk is often conducted to help guide patients' diagnosis, treatment and follow-up in the clinical environment, however current clinical motion analysis services are often financially and technically inaccessible to clinicians and therefore their patients too. This investigation aims to bench test a novel piece of motion analysis software (VOHM) against what is considered to be the gold standard in motion analysis. VOHM is a piece of 2D motion analysis software which utilises paper markers for identification of anatomical landmarks. The software then calculates parameters such as knee joint flexion angle, thigh inclination angle and shank (calf) inclination angle. These measurements can help the investigator determine if the patient's gait deviates from "normal" gait. This is to determine if a more technically and financially accessible system can provide the same standard of gait analysis. If this is shown to be the case then a more accessible method of instrumented gait analysis could be made available to health professionals and thus serve a greatly increased patient population who may benefit from assessment of their movement.

Do you have to take part?
Participants in this investigation will be required to volunteer approximately one hour of their time to perform a series of walking trials. It is under each participant's own discretion whether he or she takes part in the investigation. Participants reserve the right to refuse to participate in the investigation or withdraw from the investigation at any time without having to provide a reason. For Strathclyde students and staff: participation (or declining to take part) in this study will not affect your standing in the university in any way.

What will you do in the project?
You will not receive any payment or reimbursement for your participation. This study involves no invasive procedures, and participants will not be asked to do any high intensity exercise. Participants may be required to perform up to 20 walking trials, approximately 8m long. Participants' walking trials will be video recorded for analysis with VOHM and also recorded with the 3D motion capture software.

Participants will be required to wear tight fitting shorts or leggings with t-shirt tucked in.
Particpants will be barefoot for all walking trials.
Participants will be required to be available for their one hour appointment between the 1st and the 14th of June. The investigation will take place in the Biomechanics Laboratory in the Department of Biomedical Engineering, Wolfson Building, University of Strathclyde.
Participants walking will be assessed via both the gold-standard technique as well as VOHM
Once the data has been collected no further participation will be required.

Why have you been invited to take part?
You have been asked to participate because you are a healthy able-bodied adult. This investigation is aiming to recruit 15 participants. Participants should be able to walk at a self-determined pace without excess physical exertion or pain.

What are the potential risks to you in taking part?
This is a very low risk investigation and providing participants can complete the task outlined in the previous section there should be no risk to subjects. All small risks such as slipping and tripping will be mitigated and minimised by the researchers carrying out the study.
Please also note that if you are a member of the staff or student body of the University of Strathclyde then your participation in this study will in no way affect your standing within the institution.

What happens to the information in the project?
All data collected from this investigation will be treated confidentially and anonymously. Data will be stored on a password locked computer hard-drive and access will be restricted to the investigators only. Following the study data will be subject to conference presentation and possibly publication.
The results of this study will be submitted for presentation at scientific and clinical conferences and will be submitted for scientific and clinical peer-reviewed publication.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?

If you are happy to voluntarily participate in this study please complete and sign the consent form on the next page. If you do not wish to participate then please accept our thanks for taking the time to read this information. **Researcher Contact Details:**

Lindsay Clarke, gtb12170@uni.strath.ac.uk, 07557402054

Dr Andrew J Murphy, University of Strathclyde, Department of Biomedical Engineering, 106 Rottenrow, G4 0NW, Glasgow, andrew.j.murphy@strath.ac.uk, 01415482855

Chief Investigator Details:

Professor Philip Rowe, philip.rowe@strath.ac.uk

This investigation was granted ethical approval by the University of Strathclyde Departmental Ethics Committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Linda Gilmour, Secretary, University of Strathclyde, Department of Biomedical Engineering, Level 2, Curran Building, 0141 548 3298, linda.gilmour@strath.ac.uk

Consent Form

Name of department: Department of Biomedical Engineering
Title of the study: Comparison of a novel 2D motion analysis system to the Gold Standard in 3D motion analysis

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project
- I consent to being video recorded as part of the project
- I confirm that I meet the inclusion criteria and that none of the exclusion criteria are present
- For Strathclyde staff and students: I understand that participation (or declining to take part) in this study will not affect my standing in the University in any way.

(PRINT NAME)	Hereby agree to take part in the above project
Signature of Participant:	Date