

Comparison of Flexible Electrogoniometers to a 3D
Optical Tracking System for Measurements of Ankle
Angles During Level Walking and Running

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DEDICATION

I would like to dedicate this to the memory of my grandmother Joyce Irene Donworth.

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Thank you to my supervisor Dr. David Pearsall who has been integral to the completion of this paper with his constant constructive comments and invaluable guidance.

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ABSTRACT

Accurate measurement of joint motion is highly desirable for human gait analysis. Marker based optical motion capture is currently a gold standard in human gait studies but limited to a small field of view, exclusively in a laboratory setting. Where quantitative assessment is needed in the unconstrained environments (eg. factory floor, clinical wards), strain-gauge electrogoniometers provide portable operation and simple measurement of joint angles. These modern electrogoniometers have overcome problems associated with prior generations of fixed axis goniometers. The purpose of this study was to examine the kinematics obtained between the optically based 3D system with strain gauge based elgons, for the measure of ankle angles. Ten subjects completed 20 barefoot walking and running trials with simultaneous recording from both measurement devices. Data revealed high correlations between devices ($r^2=0.78-0.97$) and relatively small degrees of error (<2.5 degrees) particularly at slower walking speeds. Electrogoniometers may be considered as reliable and accurate devices for use in gait studies.

ABRÉGÉ

Une mesure juste et fidèle du mouvement des articulations est extrêmement importante pour les différentes études d'analyse de la démarche humaine. À ce jour, la capture optique du mouvement à l'aide de marqueurs est un standard pour les études sur la démarche humaine, mais elle est sujette à des erreurs reliées au mouvement de la peau ou au mauvais placement des marqueurs réfléchissants. Une alternative à cette méthode consiste à utiliser des électrogoniomètres flexibles. Ces derniers sont portables et plus simples d'utilisation, mais ont tendance à provoquer un niveau indésirable de rétroaction. L'objectif de cette étude est d'examiner les différentes caractéristiques de ces deux techniques durant la mesure des angles de la cheville durant le cycle de marche, ce qui permettra de tester la validité des résultats obtenus avec les deux méthodes dans les études sur la démarche humaine. Dix sujets ont complété vingt essais de marche et de course à pieds nus alors que les résultats étaient enregistrés utilisant les deux techniques. Ces résultats présentent de très forte corrélations ($R^2=0.78-0.97$), particulièrement à vitesse de marche, en plus de démontrer des différences non significatives entre les événements spécifiques à la démarche humaine.

Les électrogoniomètres peuvent donc être considérés comme des appareils justes et fidèles pour l'étude de la démarche humaine.

CHAPTER 1 BACKGROUND AND OBJECTIVES

The first record of quantitative measures of locomotion patterns dates from 1885 when the French physiologist Etienne Jules Marey (1830-1904) used chronophotographic equipment to create a stick diagram of the temporal progression of a runner (Winter 2005). Marey, a pioneer of kinesiology, in addition created many devices to quantify aspects of human motion, including elaborate systems utilizing insole air chambers to measure foot contact, a primitive accelerometer on the head, and a pneumatic-driven handheld “portable” chart recorder (Cavanagh 1990). Muybridge, (1830-1904) was a contemporary with his 1887 publication “Attitudes of Animals in Motion.” The well known photographic sequence of horse motion during a gallop was documented and initiated the early days of motion analysis. These technological developments were seminal to the field of biomechanics, particularly regarding our understanding of the mechanics involved in human walking and running.

Accurate and reliable measurement of human joint motion is essential for clinical evaluation of joint mobility or dysfunction in gait analysis. Acquired data should ideally be transferable between clinical settings and also comparable to measures published in scientific literature. In over one hundred years since Marey, motion can be quantified

relatively easily and expediently by various methods including goniometry, digital video analysis and three-dimensional motion capture. However, these descendant technologies do not necessarily produce common or equivalent estimates of movement. This issue is the motivation for the study reported here: more specifically, to compare the kinematic patterns obtained for the ankle and rear-foot using two conventional technologies: three dimensional optical tracking and flexible strain gauge electrogoniometers. The following text will provide relevant background details of these two instruments, and then elaborate on the predominant clinical concerns about the equivalence of their estimates.

1.1 Background research

Walking and running kinematics can be used to quantitatively describe how a body moves in a defined space and time. Kinematics, a branch of mechanics, describes motion of points or rigid bodies without reference to the forces that created the motions. Within the field of biomechanics, joint angular kinematics may be obtained directly using analog potentiometers (i.e. electro + goniometer) or indirectly from post-hoc calculations derived from linear body segment spatio-temporal tracking (i.e. digital motion capture).

1.1.1 Goniometry

A goniometer is simply a device that can measure angles (origin Greek: *gonia*, meaning angle and *metron*, meaning measure).

Goniometers can be used to measure local (internal) joint angles during human movement when attached across two or more joint segments. The corresponding angular output can then be used for quantitative clinical evaluation or experimentation.

Many forms of goniometers exist, ranging from the basic protractor commonly used in geometry to sophisticated electrogoniometers (electronic goniometers or sometimes referred to as “elgons”). The electrogoniometers are based on embedded circuitry utilizing potentiometers, fibre optics or strain gauges to calculate angular deviations. Electrogoniometers are advantageous over manual goniometers in that they can measure in both spatial and temporal domains producing a continuous output of angles over time. Manual goniometers are only capable of discrete readings, but do not require running wires or the use of acquisition devices; therefore, they are useful for quick assessment of maximal range of motion measures. Researchers have found electrogoniometers to be desirable over other forms of motion

capture due to their simplicity, high sample rate, and affordability (Legnani et al. 2000, Myles 2002).

1.1.1.1 Fixed Center Goniometers

I will use the term 'fixed center goniometers' to define goniometric devices that rotate about a mechanically restricted central axis. The fixed center prevents any movement of the center of rotation with respect to the measuring device (Figure 1). A potentiometer-based electrogoniometer has a fixed center of rotation. A constant DC voltage is applied to the terminals of the potentiometer that changes resistance in a linear fashion with a change in angle (Winter 2006). This device is a variable rheostat analogous to turning a volume knob on a common audio device. As the knob is turned in either direction, the resulting signal amplitude is increased or decreased as the resistance to the signal changes. Using a regression equation, signal amplitude can be calibrated to known angles. These types of fixed center goniometers require precise alignment with a joint's estimated center of rotation. As well, they may require mechanical slides to follow a non-stationary axis of rotation, as in the knee (Winter 2006).

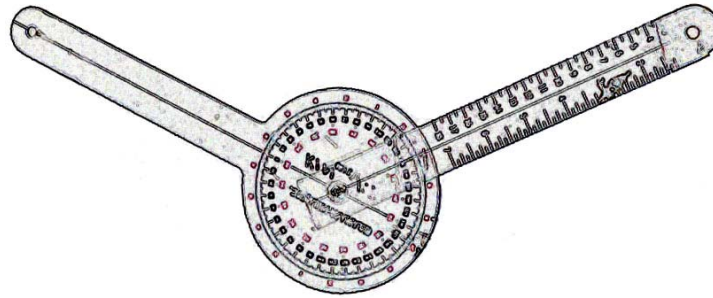


Figure 1: Diagram of a fixed center goniometer. The axis of rotation is mechanically restricted to one position in space.

1.1.1.2 Variable Center Goniometers

I will use the term 'variable center goniometers' to define goniometric devices that do not have a specific point of articulation for measurement. These devices are typically electrogoniometers based on strain gauge (Figure 2) or fiber optic technology and can be placed over a joint without the need for alignment with the exact center of rotation (Rowe et al 1989). Angles are based on relative orientation between the devices end blocks, hence, non-stationary joint center of rotations may be measured. A slight difference in placement of this type of electrogoniometer has negligible effects on range of motion measures (Ball & Johnson 1993, Tesio *et al* 1995).

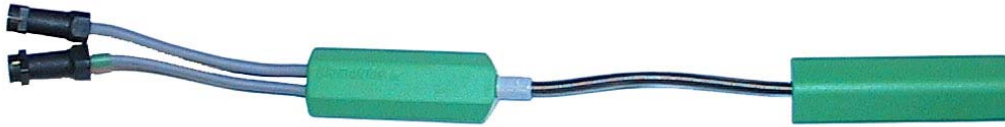


Figure 2: An example of a strain-gauge based electrogoniometer (Biometrics Ltd, Gwent, UK, Model SG110). The center of rotation between to two green end blocks is not defined (i.e. not fixed).

1.1.1.3 Mechanical Properties of the Electrogoniometer

From this point onward, the term electrogoniometer will refer specifically to a strain gauge-based variable center goniometer (Figure 2). The electrogoniometer sensing element consists of a flexible core approximately 0.3mm in diameter with four resistive wires, equally spaced around the core circumference, that run along its entirety. Each pair of opposite facing wires forms a calibrated $\frac{1}{2}$ bridge strain gauge transducer (Jonsson & Johnson 2001). One bridge measures flexion and extension of the electrogoniometer while the other measures left and right deviation (Figure 3). The symmetrical placement of the strain gauges assures the axes are orthogonal and intersect one another. A protective metal spring sleeve surrounds the sensing element to protect it from crushing while allowing flexibility. One end of the electrogoniometer sensing element is fixed to the proximal end block, while the other end utilizes a slide

mechanism to allow translation of the distal end block up to 35mm to adapt for changes in length of the secured device that could occur during joint movement. Either end of the electrogoniometer (terminal or free end) may move to register a relative angular displacement. The plastic end blocks serve as protection and provide a skin attachment point and straight reference edge for calibration of angular displacement.

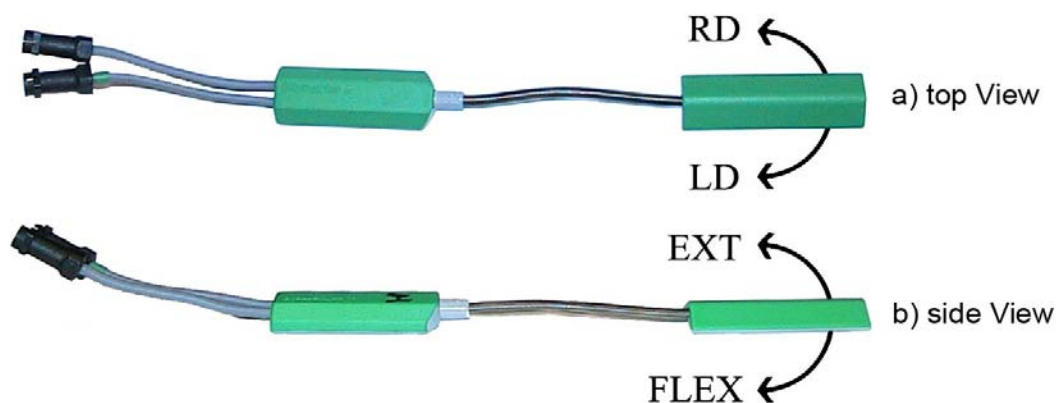


Figure 3: Definitions of the movements measured by each strain gauge transducer in the electrogoniometer. One transducer measures right deviations (RD) and left deviations (LD), while the other measures flexion (FLEX) and extension (EXT).

1.1.1.4 Limitations of the electrogoniometer

Being a novel measurement device, several studies have been conducted to ascertain the accuracy and repeatability of electrogoniometers. As a result of its design, the opposing strain gauges are sensitive to measurement errors when torsion (twisting) occurs between the end blocks (Hansson *et al*/2004, Jonsson & Johnson 2001, Legnani *et al*/

2002). The degree of this error increases directly with increasing torsion; however, Legnani *et al* (2002) stated that the maximum error from nominal position was only 3 degrees at 90° of flexion and 30° of twist. Since torsion of the end blocks creates a strain on both transducers, the reading is interpreted as movement in both measurement planes. Limited success has been achieved in attempting to correct the signal using a combination of torsionometer and electrogoniometer (Hansson *et al* 2004). It is also important that the central cable be free to move over the joint being measured. Unnatural changes in cable path, such as redirecting the cable around an obstacle or fixing a portion of the cable in place can lead to errors of 3-4 degrees (Legnani *et al* 2002). Shirarsu and Cowry (2003) tested reliability of measures between several devices of the same model (Biometrics XM150B). The researchers reported that when measurement angles exceeded 10 degrees, different sensors could produce significantly different measures of the same deviation. Hence, voltage-angle precalibration may be necessary to obtain comparable results between multiple sensors. As electrogoniometers are positioned remotely to the joint being measured (ie. on the skin's surface) confounding factors such as skin and soft tissue movement can affect the reported angles of the underlying joint (Stacoff *et al* 2000, Lu & O'Connor 1999, Seigler *et al*

2005, Milani 2000). Finally, as electrogoniometers are electrical devices they are subject to electromagnetic interference and temperature changes (average signal drift of $0.067^{\circ}/^{\circ}\text{C}$ (Biometrics 2002)). Again, depending on environmental conditions a pre-calibration may be necessary to obtain correction factors.

1.1.2 Digital Video Motion Capture

Early human motion capture involved time consuming manual digitization (i.e. numerical recording of Cartesian coordinates from film) of visually contrasting surface markers placed on the body (Winter 2006). A scaling factor would be calculated from an object of known dimensions within the film plane (the plane parallel with the camera's image sensor). This factor could then be used to transform digitized pixel units to a real world scale. From positional data, kinematic measures, such as joint angles, could be calculated using at least three point coordinates. This analysis was, however, inappropriate for joints in which rotation occurred outside the film plane. In these cases, 2D analysis will create projection errors (Areblad *et al*/ 1990) and erroneous joint angle estimates.

1.1.2.1 3D Optical Motion Capture

The augmented memory capacity and processing speed of personal computers in the mid 80's lead to a shift in recording technology from physical celluloid film to digital video formats. Personal computers were utilized not just for post processing of coordinate data but during the actual collection of the raw video. Circle fitting algorithms were developed to semi-automate the digitization of digital video coordinates. Typically, these circle fitting algorithms would detect brighter reflections in the image caused by small reflective, spherical markers attached at specific points of interest on the subject (note: these would fluoresce from light projecting coincident with the camera's optical axis). A circle would be calculated that fit around the bright area illuminated by light reflection and the resulting (x,y) coordinate of the circle centroid would be returned. Conventional commercial systems such as VIdéo CONvertor (VICON®) adopted and optimized these algorithms (Winter 2006) greatly improving the speed at which data could be extracted. Infrared light emitting diodes were incorporated into camera designs so that much of the visible light spectrum could be filtered at the camera lens eliminating many environmental artefacts caused by ambient lighting. Application of these circle fitting algorithms on multiple synchronized cameras allowed for

quantification of marker positions in three dimensions. A calibration algorithm determines the camera's position in space and allows the user to specify an origin and laboratory coordinate system. Using this camera positional information a vector ray (imaginary line projecting from the camera) is created from the initial circle fit. When two or more vector rays from different cameras intersect or come very close to intersecting, a 3D coordinate is calculated that best solves this intersection (Figure 4).

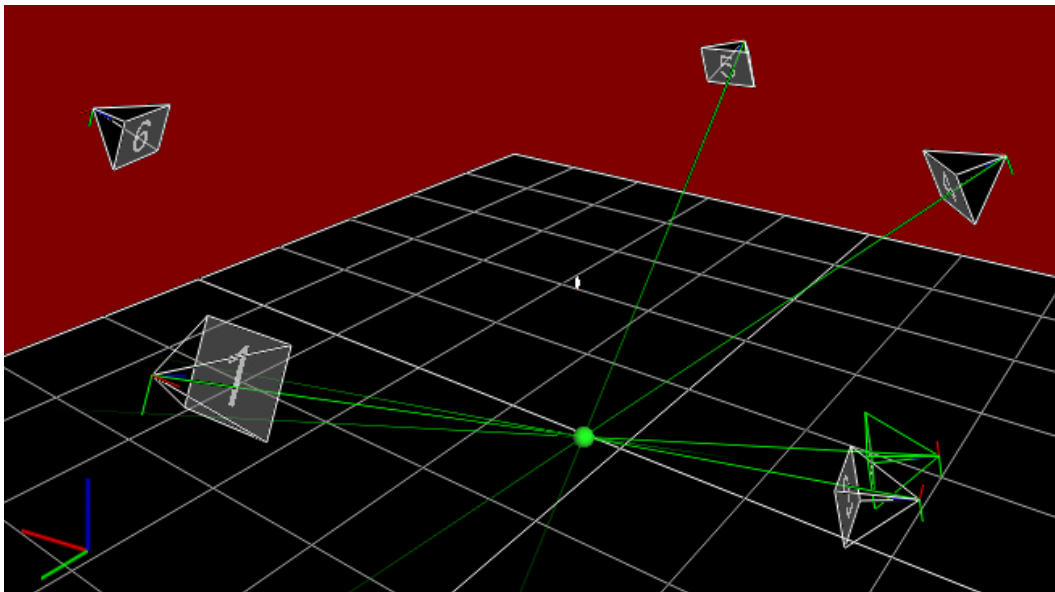


Figure 4: 3D reconstruction showing vector rays (green) projecting from each camera. The optimized intersection of these 5 rays is determined as the (x,y,z) coordinate of the 3D marker.

Modern VICON® systems utilize hardware processors for circle fitting built into each camera. This has resulted in a substantial increase in system performance, as the PC processor has less data to process before

calculating each frame. Accuracy of these systems has reach sub-millimetre precision for focused captures such as at the hand (Cook *et al* 2007). Because of their high level of accuracy and ability to compute 3D coordinates, video based motion capture systems are widely adopted in biomechanical studies (Chiari *et al*/2005).

1.1.2.1.1 Limitations of 3D Optical Motion Capture

Though modern 3D optical systems are considered a 'Gold Standard' in measurement of human kinematics, these systems have several major limitations. With the advanced electronics and multiple cameras, cost is a strong limiting factor in many laboratories (Myles *et al* 2002). Being optics based, the cameras must maintain a direct line of sight with the reflective markers. This line of sight can be easily be broken particularly in gait studies when an arm or leg swings and temporarily blocks the view of markers on the opposing limb and body. This occlusion requires use of multiple cameras to reliably track a motion especially in larger environments where a full body capture would be desirable. Though it only takes a minimum of two cameras to determine a 3D coordinate, due to the mentioned marker occlusions and line of sight requirements, higher

camera counts are desirable to maintain a complete coordinate capture. These camera systems must be calibrated before data collection and cannot be moved following the procedure, thus delimiting the 3D capture volume to the calibrated space. Also, as the field of view is increased (i.e. the camera is moved farther away) the resolution of the captured coordinates is greatly reduced, as the bright projected image from a marker reflection occupies a smaller portion of the image sensor. The accuracy of the circle fitting algorithm is highly dependent on the amount of pixel data for each marker (Vicon Online Support), thus fewer pixels results in a less accurate circle.

In vivo studies utilizing 3D motion capture typically estimate the underlying bone motion by measuring coordinates of markers attached to the skin. As with the electrogoniometers, this is problematic as the coordinates are influenced by skin motion and tissue deformation which typically overestimates underlying bone motion (Stacoff *et al*/2000, Lu & O'Connor 1999, Seigler *et al*/2005, Milani 2000). In lower body kinematics, skin mounted markers can account for upwards of 20 mm of displacement with respect to the underlying bone (Fuller et al. 1997) with motion artefacts being proportionally greater in the frontal and transverse planes than in the sagittal plane (Capozzo *et al*. 1996). At the malleolus of the

ankle (a common marker point for lower body kinematics) motion artefacts of 15 mm can occur during dorsiflexion and plantarflexion (Cappozzo *et al.* 1996). These patterns of skin displacement tend to differ from task to task and are problematic to resolve by filtering. Ignoring the effects of skin deformation is troublesome as the data obtained may affect the practical usability of the results (Capozza et al. 2005).

1.1.3 Lower body kinematics

During walking and running the only body segment that directly contacts the resisting surface (the ground) is the foot. As a result of this direct interface, the study of kinematics at the ankle and foot are particularly important. The foot represents the final link in the kinematic chain and has been subject of a wealth of scientific, clinical and industrial literature. Despite the obvious significance of ankle and foot kinematics to locomotion, it is difficult to quantify for several reasons, primarily due to its anatomical complexity. At this time, it is instructive to provide further details on the osseous composition and articulations of the foot and ankle.

1.1.3.1 The Ankle joint Complex (AJC)

The ankle joint complex consists of both the ankle (talocrural) and subtalar (talocalcaneal) joints. The ankle joint is the articulation between the talus and distal tibia/fibula and the subtalar joint - the articulation between the talus and calcaneus (Figure 5).

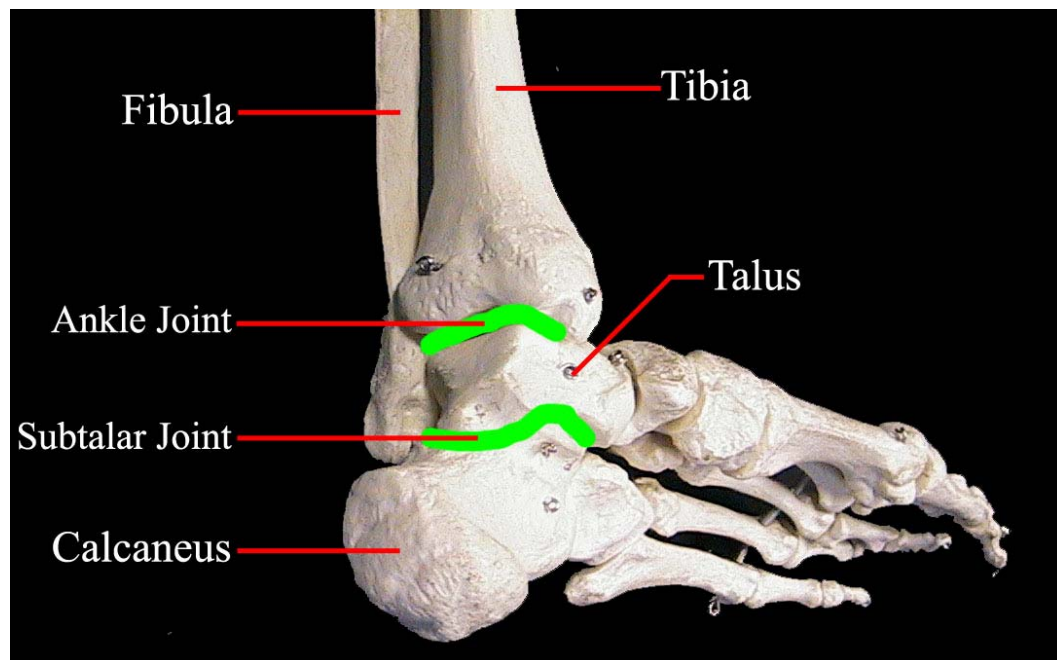


Figure 5: Osseous composition and articulations of the foot and ankle. Articulation surfaces are highlighted in green.

The ankle joint is a synovial hinge joint and is considered to have a single oblique axis with 1 degree of freedom (plantar flexion/dorsi flexion) (Levangie & Norkin 2001). The axis of rotation passes through the lateral malleolus, the body of the talus and through or just below the medial

malleolus. The range of motion of the ankle joint is typically 20° of dorsiflexion from neutral and 30-50° of plantarflexion

The subtalar joint is a composite joint formed by articulations with the talus superiorly and the calcaneus inferiorly. Description of its movements is cumbersome. In a study of 46 cadaver feet, V.T. Inman (1976 cited in Cavanaugh 1990) quantified the motions and axes of rotation for the subtalar joint. This was accomplished using a direct bone measurement of the rotating calcaneus using an implanted wire. They reported that the subtalar joint rotates about a mean axis that is directed 23° medially and tilted 42° upward. This motion is often described as triplanar, suggesting that talar bone rotates about three axes simultaneously; hence, rotations are difficult to interpret because they do not conform directly to anatomical planes. The resulting motion of the subtalar joint about its oblique axis is referred to as abduction and adduction. If, however, we describe this motion in terms of the anatomical planes, the adduction is a combination of inversion and plantar flexion where as abduction a combination of eversion and dorsi flexion. Compounding the difficulty in dividing foot and ankle kinematics are the coupling movements that occur with the lower limb (i.e. leg or shank) such that subtalar adduction and abduction produce concomitant external and

internal leg rotation. Furthermore, the proximal-distal sequence of movements changes depending on whether the limb is free or weight bearing (Rau *et al* 2000).

1.1.3.2 Quantifying AJC Angles

Either of the aforementioned methods can be used to estimate motion at the AJC. The electrogoniometer can be positioned parallel to the Achilles tendon and the rearfoot (calcaneus) to measure changes in angle between the calcaneus and tibia/fibula. With the optical motion capture system, three or more markers are attached to each segment to define the rigid body's orientation from which joint angles can be calculated.

Humans typically wear some sort of protection (shoes) over the foot when performing walking or running tasks. This creates difficulty in quantifying underlying bone movement because the shoe is a deformable object and some foot sliding may occur inside. Measures of ankle kinematics derived from placing instruments on external footwear may overestimate the underlying joint motion in some instances, and obscure others. This is confirmed for both electrogoniometers mounting in-shoe and on-shoe (Milani 2000), and for motion capture (Reinshchmidt *et al* 1992). Milani reported a 1.5 degree reduction in the range of motion using

in-shoe versus on shoe method and a 19% decrease in angular velocity. During a lateral stepping exercise, Reinschmidt recorded an average range of heel inversion of 13.3° from markers placed directly on the unshod foot and 30.7° using markers placed directly on the shoe. In optical motion capture, the markers are difficult to place on a shod foot (Pohl *et al*/2007) as you must estimate the location of anatomical features from outside. Reinschmidt and associates reported that for lateral movements, shoe-mounted markers do not accurately represent the movement of the heel inside the shoe. Reinschmidt suggested that observing optical markers directly on the foot through 'windows' would give better indications of the calcaneous motion. To avoid the interference of the footwear, other researchers have either cut away the heel counter, the rearmost portion of the shoe, (O'Connor *et al*/2002), or utilized shoe models that are designed without a heel counter (MacLean *et al*. 2006). These methods may cause slight changes in the resulting kinematics, especially if the subject is not accustomed to such footwear variations. Given that foot models must simplify the motions of 28 bones forming 25 component joints (Levangie & Norkin 2001), an unbiased understanding of foot kinematics is difficult due to the complexity of the foot structure (Carson *et al*/2001).

1.1.3.3 The Conventional Gait Model (CGM) and Optimized Lower Limb Gait Analysis (OLGA)

The Conventional Gait Model (CGM) (Davis *et al.* 1991, Kadaba *et al.* 1990) utilizes a modified Helen Hayes marker set of 16 markers on the hips and lower limbs. Given the coordinates of these markers lay external to underlying bone and tissue, several mathematical equations (Appendix I) are used to estimate the true joint centers. The four markers situated around the hips (Appendix II) are used to create a hip local coordinate system. A regression equation (Davis *et al.* 1991) is used to specify the location of the hip joint center in this local coordinate system. Femur segments are defined by these hip joint centers lateral thigh markers (LTHI/RTHI) and the lateral knee markers (LKNE/RKNE). Tibia segments and ankle joint center are defined by the knee joint center, lateral tibia markers (LTIB/RTIB) and the lateral malleolus markers (LANK/RANK).

OLGA (Optimized Lower-limb Gait Analysis) acts as a Plug-In, compatible with Vicon Workstation software. OLGA co-exists with the Conventional Gait Model implemented by Vicon in the Plug-In Gait software packages. Plug-In Gait calculates estimated joint centers on a frame-by-frame basis using the algorithms adopted from the CGM (Roren 2005). OLGA, however, introduces an additional step to optimize the

locations of these joint centers across time. The pipeline process of the OLGA starts by first using the CGM's static trial (standing trial) to calculate an initial estimation of joint center locations and segment orientations. A dynamic trial, for example a sample walking trial with multiple strides, is then used to calibrate the rigid body model. This calibration utilizes the initial estimates for joint centers provided by the CGM and optimizes their locations for the recorded trial based on a statistically based process. This calibrated model is then used for kinematic fitting to movement data. This process finds segment orientations that best fit the motion capture data, effectively reducing marker noise and skin motion artifacts as there is no longer such a strong constraint on the measured marker positions. Finally, the results are smoothed across time using a Kalman filter (Kalman 1960).

1.2 Rationale for the study

Accurate measurement of joint motion is essential in human gait analysis. Kinematic data are used extensively for analysis of human motion regarding performance, assessment and rehabilitation.

Researchers aim to reproduce testing conditions as closely as possible to the actual movements carried out during the studied task, for example,

walking. Due to the limitations of marker occlusion in optical motion tracking systems, however, problems may arise with regard to marker placement when subjects use footwear. Electrogoniometers provide several advantages as alternative measures to optical systems, namely when footwear must be worn or larger, non-confined capture volumes are required. Thus, the measurement accuracy of electrogoniometers within the range of motion of the ankle joint complex during walking and running is important to define in order to relate the two measurement methods.

1.3 Objectives and Hypotheses

The purpose of this study is to provide validation of electrogoniometers (elgons) by direct comparison with a popular 3D motion capture system. The ability of both systems to measure the unique range of motion at the ankle joint complex during normal walking and running gaits will be evaluated. This evaluation will consist of three distinct phases:

I) Determine the precision of the elgon based on its ability to report known angular deviations of a fixed-center goniometer.

II) Determine the precision of the Vicon system in its ability to report within a calibrated capture space, the known angular deviations of two marker triads mounted to a fixed center goniometer.

III) Compare rearfoot elgon angle measures within the specific context of walking and running to synchronized Vicon measures of markers triads mounted directly to the device. In addition elgon measures will be compared to modeled AJC angles calculated using the Plug-In Gait/OLGA pipeline, a widely accepted clinical gait model.

The Vicon system is expected to provide accurate measures of triad angles within the central calibration space. Increased error is expected closer to the periphery of the calibration space as fewer cameras maintain a direct line of sight of the markers. Secondly, the elgon is expected to correlate highly to the manual goniometer as there is no torsion applied and the manufacturer states an error of 2°. Secondly, the elgon measures are predicted to correlate very highly with the optical based-measures of triads mounted on the goniometer, taking into account the error involved in both systems. Finally, the elgon AJC angles are predicted to correlate highly (>0.7) with the Vicon modeled ankle joint

motions of dorsi and plantar flexion. Inversion and eversion are expected to correlate to a lesser degree, due to the complexities of the joint motion and reduced range of measurement.

CHAPTER 2 - METHODS AND PROCEDURES

2.1 Experimental Procedure

A flexible electrogoniometer (Biometrics Ltd, Gwent, UK, Model SG110A) was modified by attachment of a rigid plastic rail to each end block. These rails served as attachment points for two 14mm diameter reflective markers spaced 55 mm apart. Six markers were adhered to the electrogoniometer in order to form two marker triads: one corresponding to each segment of the electrogoniometer (Figure 7). Triads were chosen to mark the segments since a minimum of three markers are required to calculate any three dimensional plane.

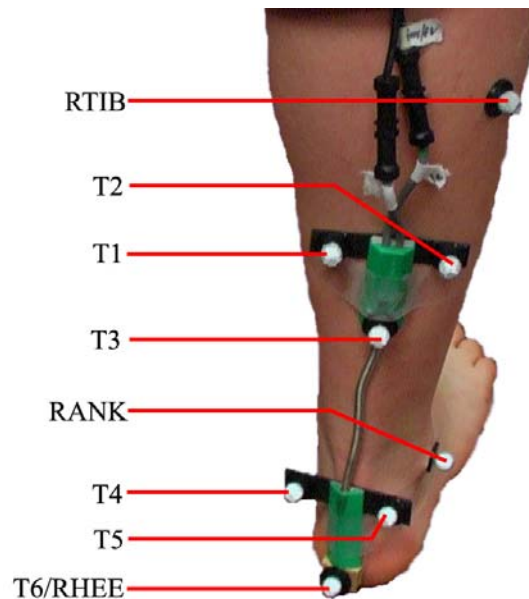


Figure 6: Marker placement on the electrogoniometer and lower leg. Note the shared marker T6/RHEE used in both the elgon triad and Plug-In Gait marker set.

By calculating the change in orientation of one plane relative to the other, we then know the orientation of one end block relative to the other, which is exactly what the electrogoniometer outputs. Thus, the signals from the electrogoniometer can be directly compared to angles calculated from 3D motion capture coordinates. Before this direct comparison, each system was independently tested to verify its accuracy.

2.1.1 Phase I

The modified electrogoniometer (with attached triads) was adhered directly to a manual fixed center goniometer such that one segment could be rotated relative to the other by a known number of degrees. Two designs of this apparatus were constructed. The first design placed the triads parallel to the flat face of the goniometer. A change of angle of the manual goniometer would simulate the movement incurred by the electrogoniometer mounted to a human foot during inversion and eversion of the AJC. The electrogoniometer was attached to a portable data logger (DataLOG model P3X8, Biometrics Ltd, Gwent, UK) sampling at a rate of 100 Hz and resolution of 13 bits. Ten 5 second trials were collected for the following angular deviations of the manual goniometer: -20°, -10°, 0°, 10°, 20°. Between each measure the goniometer was rotated

roughly 90°, then placed back to the specific collection angle to avoid any potential biases caused by goniometer misalignment, and to allow the electrogoniometer cable to assume a natural path for each collection.

The second design of the testing apparatus placed the marker triads perpendicular to the flat surface of the manual goniometer. A change in angle of the manual goniometer would simulate the movements incurred by the foot-mounted electrogoniometer during dorsiflexion and plantarflexion of the AJC. Ten 5 second trials were collected for the following angular deviations of the manual goniometer: -40°, -20°, -10°, 10°, 20°, 40°. The same testing procedure was followed as in the first apparatus.

2.1.2 Phase II

The accuracy of the motion capture system was evaluated with the same testing apparatuses used in Phase I. Each apparatus was mounted to a rigid pole approximately 1.5m long. The pole allowed for the apparatus to be tightly secured for the set collection angle and be moved throughout the capture area of the 3D system. A Vicon® 460 motion capture system with six MCam2 near-infrared cameras was used to collect ten 30s trials for each goniometer deviation. The first apparatus design

was tested for deviations of (0, $\pm 5^\circ$, $\pm 10^\circ$) and the second design for (0, $\pm 10^\circ$, $\pm 20^\circ$, $\pm 40^\circ$). Data were collected at a rate of 100Hz.

2.1.3 Phase III

2.1.3.1 Electrogoniometer preparation

The electrogoniometer with attached triads was adhered to the rear of the AJC on the right foot (Figure 7). The subject's skin surface was first wiped with an isopropyl alcohol pad followed by a light covering with adherent tape spray to prevent unwanted shifting of the electrogoniometer.

Double-sided tape was used between the electrogoniometer and subject's skin. Several strips of inch-wide non-elastic athletic tape were placed over the electrogoniometer endblocks and surrounding tissue to secure the device in place. Two signal wires were run through the leg of pair of athletic spandex tights and then into a small pack carried around the subject's shoulders. A 0.5" circular force sensitive resistor (FSR, #402, Interlink Electronics, Camarillo, CA) was adhered to the heel using tape and force captured through the digital input of the data logger to assist in determination of stance phase.

2.1.3.2 Motion Capture Preparation

The Vicon® 460 system was calibrated in ViconIQ 2.5 using a 240mm wand and 14mm static L-frame. The wand serves to calibrate the cameras orientation relative to each other, and also correct for any lens distortion. By waving the wand through the entire capture space, the active portion of each camera sensor is calibrated to a known real distance. The L-frame serves to mark the 3D workspace origin and define the coordinate system. For each trial, +X was defined as the walking direction, +Y facing the subject's left and +Z facing upwards. A maximum error of 1.5mm was established as a requirement to accept the calibration and continue with capture. Before attachment of the electrogoniometer to the subject's foot, a trial was captured with the electrogoniometer and triads mounted on a level turntable (Figure 8). The purpose of this trial was to align the local coordinate system of the electrogoniometer mounted triads with the global/laboratory coordinate system set by the Vicon capture system. It was ensured that the electrogoniometer lay flat on the turntable surface and that the edges of the electrogoniometer were parallel with the top grid surface. The length of the electrogoniometer was roughly aligned with the x-axis of the 3D capture space. During a capture

the turntable was rotated approximately 10° back and forth to ensure a frame could be captured in which the coordinate systems were very closely aligned.

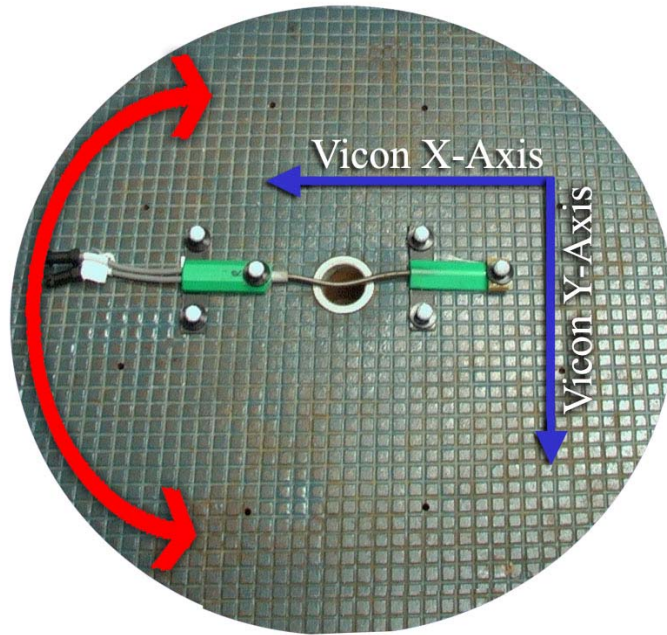


Figure 7: Electrogoniometer placed flat on the turntable for triad calibration. Red arrow indicates directions of rotation.

The Vicon® Plug-In Gait lower body marker set was used in addition to the markers on the electrogoniometer. 14mm reflective markers were placed on both lower limbs at the posterior iliac crest, anterior iliac crest, thigh, knee, tibia, lateral malleolus, heel and toe (Appendix II). Due to the electrogoniometer physically covering the heel of the foot, the inferior electrogoniometer marker also served as the heel marker. This should have no effect on the resulting ankle angles calculated by Vicon, as the foot is treated as a rigid segment and

orientations of the segment, not positions of the marker are used in calculations (Plug-In Gait Model Details, Vicon Online Support). It was ensured that the shared heel marker and toe marker were placed at the same height to conform to the model requirements.

2.1.3.3 Synchronization

Data synchronization was achieved by a simultaneous push button event detected by use of a force sensitive resistor (FSR) switch attached to the portable datalogger and a 5V mechanical trigger collected through the Vicon® 460's analog signal input. As a force is applied to the FSR, the electrical resistance to the incoming signal changes. The change in resistance is highly correlated to a change in force. A threshold resistance was manually programmed into the datalogger to trigger an on/off event. The threshold was adjusted such that the event would not be triggered until the push button was fully depressed. Before and after each trial the FSR was placed over the push button which was then firmly pressed for approximately 1s and quickly released. The falling edge of the signal was used to synchronize both systems as the rising edge was more prone to human error. Both systems collected at the same sampling rate (100Hz). A methodological map for collection is presented in Appendix III.

2.1.3.4 Collection

Subjects were instructed to stand comfortably within the 3D capture space for approximately 30s. During this time, both channels of the electrogoniometer were zeroed to this standing position. At the same time, the coordinates of the markers were captured to create a static reference for the triad angles and also for static calibration of the PlugIn Gait model. Following static collection, subjects performed 15 walking and 20 running trials.

2.2 Subjects

2.2.1 Calculation of Sample Size

A statistical analysis program (JMP 4.0.4, SAS Institute, USA) was used to calculate subject sample size using initial measures obtained from pilot data. Using a detectible difference of 2 degrees (based on the published $\pm 2^\circ$ error of the elgon) and predicted standard deviation of 1.42° (based on pilot data from two subjects), a minimum of 8 subjects was deemed necessary obtain a power greater than 0.85 at an alpha level of 0.05 (Figure 6). Ten subjects were recruited in the event of a dropout or problematic data.

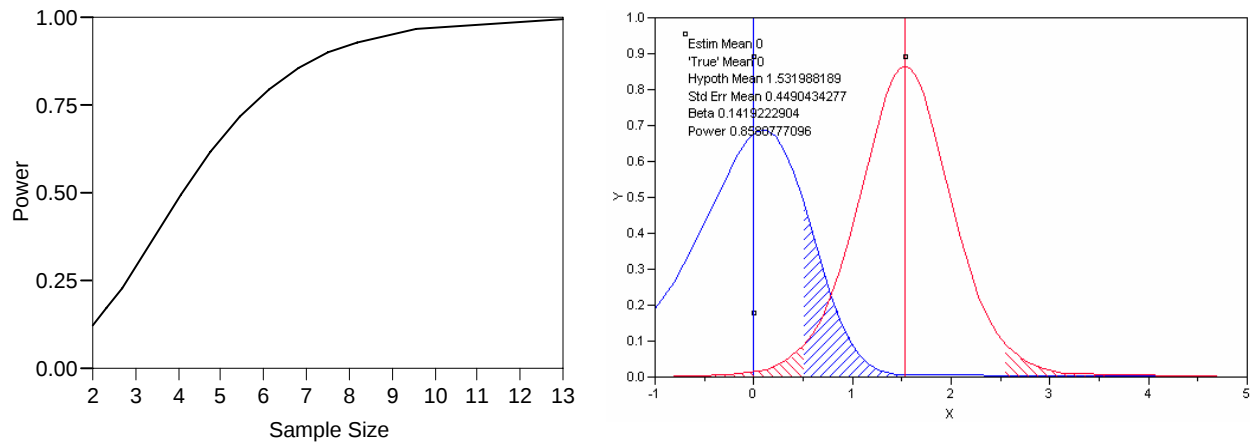


Figure 8: Power plots based on initial pilot data for the experiment. A minimum of 8 subjects were deemed necessary to obtain a power of greater than 0.85 (Left). With a sample size of 10 a detectable difference of 1.5 degrees is possible while maintaining a power of 0.85 (Right).

2.2.2 Subject Recruitment

Ten adult subjects (18-40 y.o.) voluntarily participated in the study. Subjects provided written informed consent following ethics approval of the institution (Appendix IV). Subjects completed a brief medical history questionnaire which acted as a screening process. Exclusion criteria included the presence of any lower limb surgery, recognized gait abnormality or muscular dysfunction or injury to the lower limb pelvis or trunk. Subjects were recruited at McGill University the Department of Kinesiology and Physical Education. Anthropometric measures were obtained for each participant (Appendix V) as part of the requirements for the 3D joint modelling software.

2.3 Data Acquisition and Processing

2.3.1 Electrogoniometers

Data collected from the electrogoniometers and FSRs were in a proprietary .RWX format written to a Secure Digital (SD) flash memory card onboard the Data logger. Biometrics software (DataLog v.3.0) was used to import the .RWX files and save them as binary .LOG files. A script (Get_Gonio.m) was written in Matlab® 7.2 (MathWorks, Inc. Natick, MA) to read the .LOG format for easier direct access to the readings. This script also applied a 4th order low-pass Butterworth filter (8Hz).

2.3.2 Motion Capture

Motion capture data were collected using Vicon® Workstation 4.6. Workstation saves 3 files for each capture: a .TVD file containing 2D circle data from each camera, a .VAD file containing synchronized analog data, and an AVI file streamed via Firewire (IEEE 1394) connection from a digital video camera.

The first trial processed was the mechanical axis trial from the spinning turntable. The .TVD file was imported into ViconIQ 2.5 where it was reconstructed and labelled in 3D. A two segment rigid body model (.vst) was created in ViconIQ which was calibrated to the dimensions of

the triads and saved as a scaled model file (.vsk). This model was then applied to the motion capture markers using ViconIQ's built in kinematic fitting algorithm which minimized the error between the actual marker positions and the rigid model, in effect filtering the data to obtain smoother plots.

Following collection of all trials, 3D trajectories were reconstructed and labelled from the .TVD file using ViconIQ 2.5. Gaps (i.e. missing marker coordinates) in trajectory data are inherent in dynamic 3D capture and must be treated appropriately. Gaps shorter than 20 frames (0.2 sec) were filled in ViconIQ using a built-in spline function, however, larger gaps were filled based on a calibrated lower limb model using the kinematic fit function. As with the triad model, this algorithm fits a rigid body model based on the commonly used Helen Hayes marker set to recorded marker coordinates in a manner that minimizes the error between the modelled and actual marker coordinates. Large gaps (>20 frames) can then be filled from a combination of the actual and modelled marker positions. Large gaps were only filled for the markers on the left leg, as interpolated trajectories would have no effect on the right leg parameters of interest. If gaps larger than 20 frames existed for any markers located on the right leg, the trial was excluded from the results. In addition to the lower limb

model, the triad model was fit to just the markers on the electrogoniometer and corresponding Euler angles were exported to a (.CSV) file format. The fully labelled trajectories were exported in .C3D format, to be read by Workstation.

A Matlab script Get_Euler.m was written to take the Euler angles output by Vicon IQ and convert them to local angles directly comparable to the electrogoniometer output. This script involved transformation of Euler angles to unit vectors (Kwon3D 2005) in order to transform them to the global coordinate system. The unit vectors were then converted back to Euler angles for statistical comparison. The script also subtracts the calculated standing trial offsets at the same time. All processed trials were run through the Get_Euler script and saved as .CSV files.

The C3D standing trial was imported into Vicon Workstation where a subject file was created and required anthropometric measurements for the Plug-In Gait model were input (Appendix V). The subject file was calibrated and saved for later processing of the walking and running trials. This calibration estimates position of joint centers based on several published algorithms (Appendix I)

Processing of the walking and running trials in Workstation began by re-linking the analog data to the newly labelled C3D data from Vicon

IQ. The Optimized Lower-Limb Gait Analysis (OLGA) pipeline was then executed to calculate joint kinematics. The calculated joint angles and analog data were exported to a single .CSV file for each trial.

A MatLab Script (Data_Sync.m) was written to compile and synchronize the contents of the electrogoniometers (.LOG), Vicon® analog data (.CSV), Right Angle Angles from OLGA(.CSV), and Triad Euler Angles (.CSV). The script automatically detected the falling edge of the FSR synchronization channel in the (.LOG) file and aligned it with the falling edge of the Vicon® Analog Channel (.CSV). These frame detections were manually inspected to ensure a good falling edge was present. The standing trial offset angles were also subtracted from each trial. Following successful synchronization the data were saved as a processed file (*.PRO).

“Zoo”, a data browser/editor program in the Matlab “O” suite was used to cut the .PRO file to a single walking or running stride and manually identify key events for each signal in each trial for discrete statistical analysis. The events markers in the three plantar/dorsi flexion channels were PF1,PF2, DF1 and DF2. In the three inversion/eversion channels events were labelled IN1,IN2, and EV1.

2.3.2 Statistical Analysis

2.3.2.1 Phase I and II

Descriptive statistics were used for the first and second phase to report the standard error of measurement between the two measurement methods (electrogoniometer and Vicon triads) and the independent variable (manually set goniometer angle).

2.3.2.3 Phase III

Statistical analysis of second phase included correlation analysis for the three output signals (electrogoniometer, Vicon Triads, and Vicon OLGA model). Since there are multiple responses for each subject, the discrete point analysis utilized a repeated measures MANOVA design. The repeated measure is treated as device, as they are both measuring the same variables of ankle angle.

CHAPTER 3 - RESULTS

3.1 Electrogoniometer and Vicon Precision Testing

Root mean squared error (from manually fixed axis goniometer angle, $n=10$) was calculated for both the electrogoniometer and optical triad method of measurement at multiple angles along two rotational axes (Figure 9).

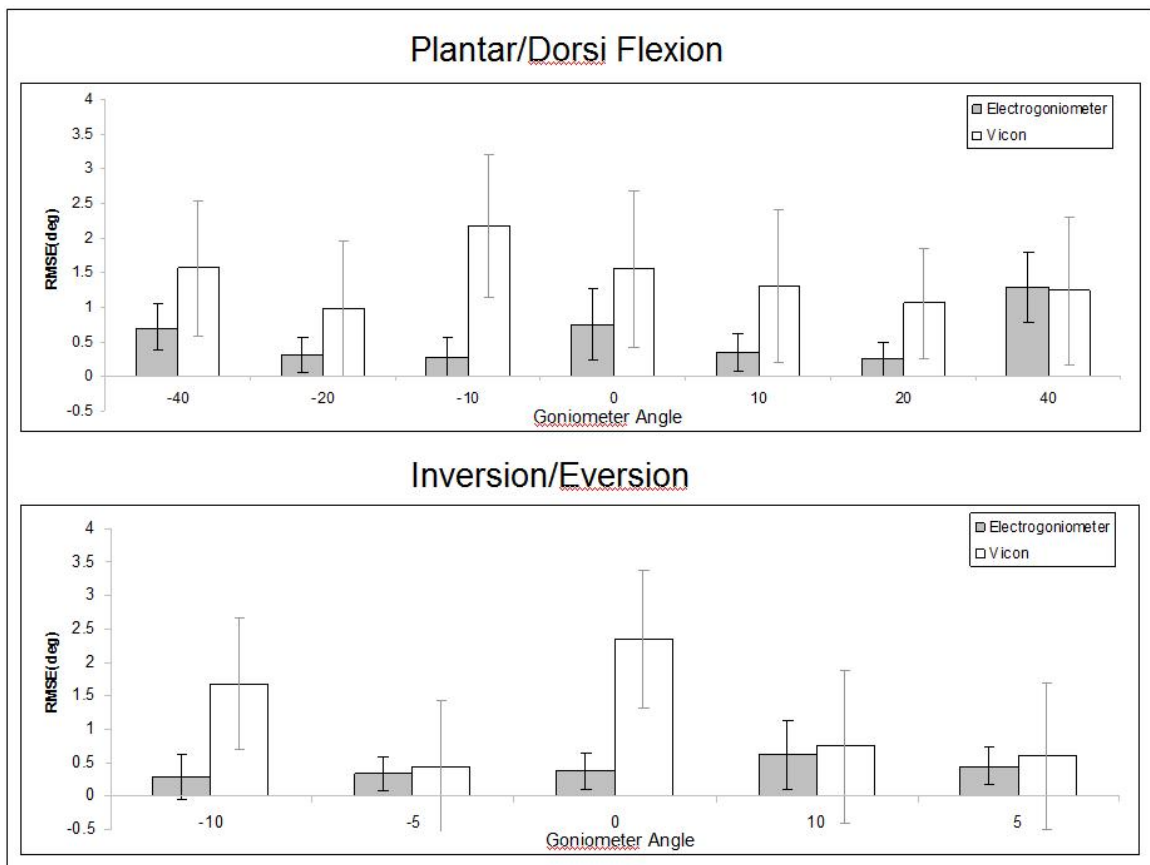


Figure 9: Mean measurement error ($n=10$) of the electrogoniometer and motion capture systems during recording of known angles defined by a fixed-center goniometer. Both systems were tested for various angles in each plane of rotation that would correspond to plantar/dorsiflexion (Pf/Df) and inversion/eversion (Inv/Ev) of the foot. Error bars are S.D.

The RMSE of the elgon ranged from (0.2 to 1.3°) from the manual goniometer angle. The RMSE of the Vicon® triad method ranged from (0.4 to 2.3°). Standard deviations of the measures were noticeably smaller for the elgon in comparison to the triad method.

3.2 Signal correlations and discrete point statistics

Visual inspection of the three output signals revealed very high correspondence between the electrogoniometer and triad derived signals. The discrete points used for statistics (PF1, PF2, DF1, DF2, IN1, IN2, EV1) based on local minimum and maximum values were identified successfully in all trials (Figure 10).

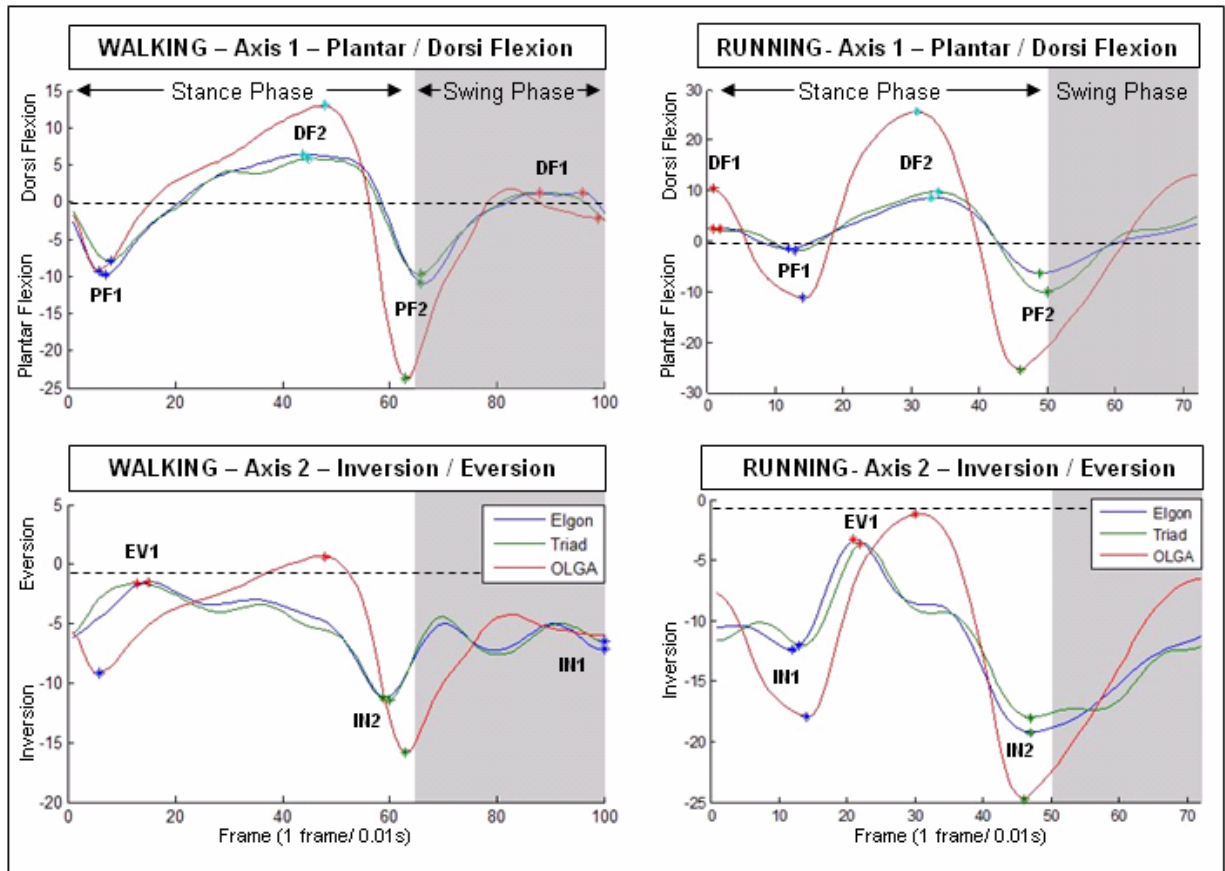


Figure 10: Representative subject's kinematics for the measurement methods including electrogoniometer (Elgon), reflective markers mounted to electrogoniometer (Triad) and the Plug-In Gait/OLGA model (OLGA). The Elgon and Triad measures correspond well to each other, however the OLGA model output quite different angles. Key events analyzed (asterisks) represent maximum or minimum angles during stance phase.

The modelled Plug-In Gait/OLGA angle amplitudes were generally quite different from the other signals, though mean (n=9) correlations of the raw signal outputs ranged from R^2 values of (0.69-0.97) (Figure 11). Signal correlation was greatest between electrogoniometer and triad signals in the plantar/dorsi flexion axis during walking. Increasing speed of locomotion from walking to running both decreased the R^2 value and increased the signal variance about both Pf/DF and In/Ev axes.

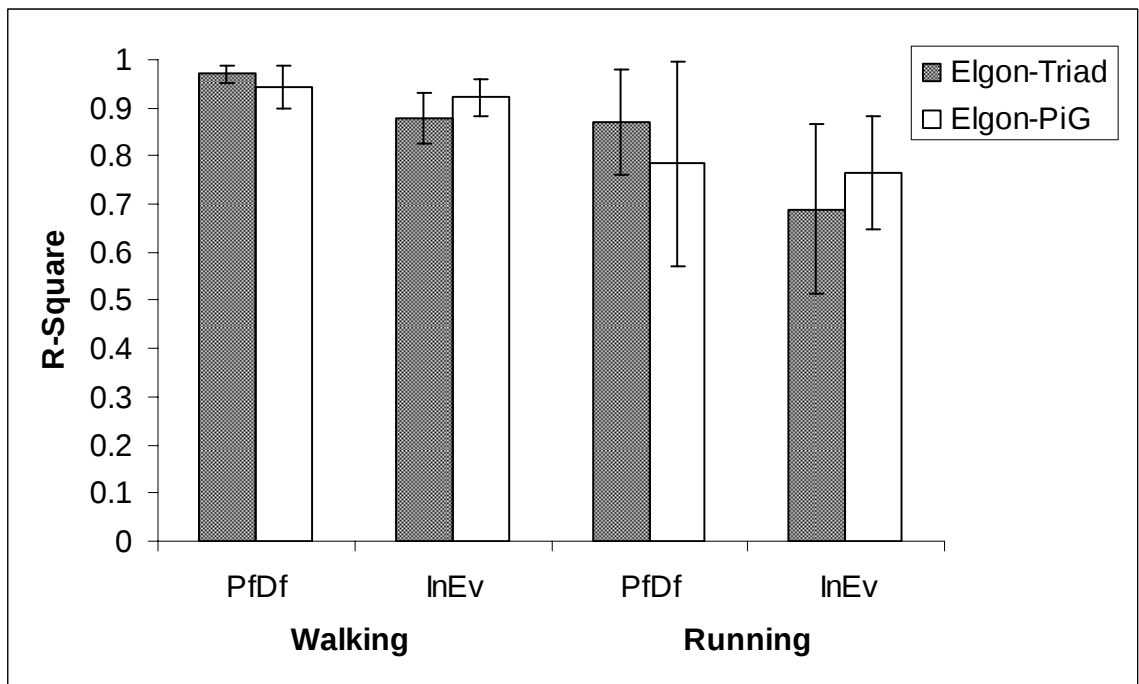


Figure 11: Mean R-square values (n=9) for the correlation of electrogoniometer and Vicon triad measures (shaded) and electrogoniometer and Vicon Plug-In Gait model (white) for walking and running speeds. Each of the 9 subjects completed 5-10 trials of walking and running. P-values for correlations were all <0.0001 . Error bars represent standard deviation.

Discrete point analysis for selected events during walking (Table 1) reveal significant differences between the electrogoniometer and triad methods at DF2, PF2, IN1 and IN2 events (Figure 10), though mean differences were relatively low between the devices, ranging from 0.2° to 2.2° (Table 1). While running PF1 and IN2 events were significantly different between devices (See Appendix VI for individual plots by event). Discrete point comparison between the electrogoniometer and the modelled Vicon Plug-In Gait/OLGA output (Table 2) revealed numerous significant differences between mean measurement values of the two methods that ranged from 3° to 22.4°. The only non-significant difference was at the PF2 event with means being identical at 13°.

Table 1: Repeated measure-MANOVA results for the comparison of electrogoniometer and optical triad methods of ankle joint measurement at key events in walking and running gaits. Each least squared mean originated from the mean of 9 subjects, each of whom completed 5-10 trials of both walking and running. (Note: Fig 1 Pf/Df y-axis was flipped for conventional display purposes). Data are mean (s.d).

Walking (Electrogoniometer vs Vicon Triads)					
Event	LS Mean° Elgon, n=9	LS Mean° Triads, (n=9)	Difference (°)	d.f.	p-value
DF1	-0.4 (0.48)	-0.7 (0.37)	0.3	(1,8)	0.0552
PF1	12.8 (1.46)	13.2 (1.36)	0.4	(1,8)	0.2383
DF2	-2.9 (0.44)	-4.1 (0.24)	1.2	(1,8)	0.0002
PF2	13.0 (1.45)	10.8 (1.49)	2.2	(1,8)	<0.0001
IN1	-4.4 (0.55)	-4.7 (0.48)	0.3	(1,8)	0.0337
EV1	1.6 (0.88)	1.8 (1.66)	0.2	(1,8)	0.5358
IN2	-7.4 (1.44)	-6.8 (1.24)	0.6	(1,8)	0.0052
Running (Electrogoniometer vs Vicon Triads)					
Event	LS Mean° Elgon, n=9	LS Mean° Triads, (n=9)	Difference (°)	d.f.	p-value
DF1	-2.9(0.38)	-3.9(1.22)	1.0	(1,8)	0.0844
PF1	4.2 (0.79)	6.3 (2.88)	2.10	(1,8)	0.0493
DF2	-5.5 (0.57)	-4.4 (1.2)	1.1	(1,8)	0.0577
PF2	11.6 (4.27)	11.0 (3.70)	0.6	(1,8)	0.1937
IN1	-5.8 (0.58)	-6.7 (1.19)	0.9	(1,8)	0.0953
EV1	1.3 (0.92)	0.9 (1.17)	0.4	(1,8)	0.4617
IN2	-8.6 (2.40)	-7.1 (1.87)	1.5	(1,8)	0.006

Table 2: Repeated measure-MANOVA results for the comparison of electrogoniometer and Vicon® Plug-In Gait/Olga modelling methods of ankle joint measurement at key events in walking and running gaits. Each least squared mean originated from the mean of 9 subjects, each of whom completed 5-10 trials of both walking and running. (Note: Fig 1 Pf/Df y-axis was flipped for conventional display purposes). Data are mean (s.d).

Walking (Electrogoniometer vs Vicon Plug-In Gait/OLGA Model)					
Event	LS Mean° Elgon, n=9	LS Mean° PiG, n=9	Difference (°)	d.f.	p-value
DF1	-0.4 (0.48)	4.3 (0.49)	4.7	(1,8)	<0.0001
PF1	12.8 (1.46)	12.2 (1.38)	0.6	(1,8)	0.0077
DF2	-2.9 (0.44)	-4.1 (0.77)	1.2	(1,8)	<0.0001
PF2	13.0 (1.45)	20.8 (1.41)	7.8	(1,8)	<0.0001
IN1	-4.4 (0.55)	-5.4 (0.79)	1	(1,8)	0.0109
EV1	1.6 (0.88)	1.2 (0.60)	0.4	(1,8)	0.2179
IN2	-7.4 (1.44)	-8.2 (0.72)	0.8	(1,8)	0.0794
Running (Electrogoniometer vs Vicon Plug-In Gait/OLGA Model)					
Event	LS Mean° Elgon, n=9	LS Mean° PiG, n=9	Difference (°)	d.f.	p-value
DF1	-2.9(0.38)	-2.3 (1.04)	0.6	(1,8)	0.1035
PF1	4.2 (0.79)	6.1 (1.67)	1.9	(1,8)	0.0013
DF2	-5.5 (0.57)	-20.1 (1.46)	14.6	(1,8)	<0.0001
PF2	11.6 (4.27)	24.8 (4.21)	13.2	(1,8)	<0.0001
IN1	-5.8 (0.58)	-5.2 (1.17)	0.6	(1,8)	0.1788
EV1	1.3 (0.92)	2.8 (1.17)	1.5	(1,8)	0.0055
IN2	-8.6 (2.40)	-11.2 (1.93)	2.6	(1,8)	0.0001

CHAPTER 4 DISCUSSION AND CONCLUSION

The evaluation of measurement devices within specific tasks and environments is essential to determine the confidence in the validity of research outcomes. Manufacturers will often provide an expected measurement error for their respective devices, however, this is a generalized level of error that may not translate equally to all movement contexts and body regions. This study was conducted to evaluate the relationships between signal outputs of flexible electrogoniometers and a 3D motion capture system specifically for the measurements of ankle angles.

4.1 Static Angle Testing

Validation studies have tended to evaluate devices such as elgons and motion capture systems by use of high precision manual goniometers integrated into a static calibration jig. Using such jigs, various angles can be adjusted precisely and the device output calibrated (Hansson et al. 2004, Jonsson & Johnson 2001). However, this form of validation may not extrapolate to the dynamic responses: that is, movement involved during human subject testing could degrade measurement accuracy as compared to static estimates.

4.1.1 Vicon® Motion Capture System

The error of the 6-camera Vicon® system was calculated as less than 2.5 degrees using the explained triad method. This calculated level of error is greater than what has typically been reported by accuracy studies using similar systems (Capozzo *et al.* 1996). The error caused by the 3D measurements can occur in multiple stages. The quality of circle fitting could affect the two-dimensional coordinates of the centroid (best fit circle over pixels illuminated by the light reflected from a marker) calculated for each camera. As markers overlap in the field of view (Figure 12) the quality of the circle is reduced and corresponding three dimensional precision in centroid location is affected. In turn, angular estimates calculated from multiple marker centroids would accrue greater error.

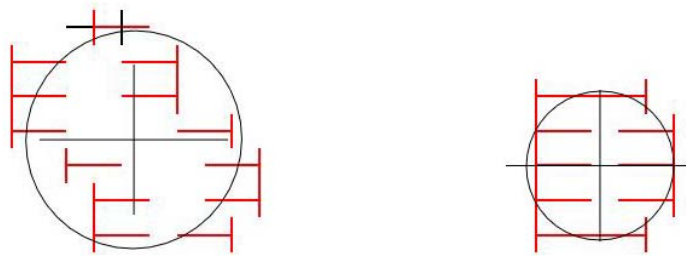


Figure 12: Vicon circle fitting errors. On the left is a correct circle fit around a single marker reflection. On the right is a case where two markers have overlapped in the field of view, but are still within the constraints of the circle fitted, thus an incorrect centroid has been reported.

4.1.2 Electrogoniometer

The electrogoniometer had a lower RMSE than the triad method in all but one case. The calculated RMSE for the elgon was below the manufacturer's stated error of $\pm 2^\circ$ (Biometrics 2004). The effects of acceleration on the change in cable path appeared to be minimal given the measurement error was maximally 1.3° . Legnani *et al.* (2000) attributed changes in cable path for upwards of $3\text{--}4^\circ$ of error, thus there were no likely events of cable path manipulation. The electrogoniometer had a lower variance than the Vicon® triads' estimates. This was likely a result of more consistent accuracy for the elgon throughout the capture space. Since the electrogoniometer readings were unaffected by position in the capture space, the readings fluctuated less creating a tighter standard deviation.

4.2 Signal Analysis

Following static testing of known angles, it was important to relate the two systems directly to each other for dynamic measures of walking trials, where the variable of angular displacement could no longer be controlled.

4.2.1 Correlation between devices

Correlation of signals for the electrogoniometer and motion capture triads revealed a strong relationship. The correlations between electrogoniometer and triad were greatest in the plantar/dorsi flexion axis. This is consistent with findings by other authors that have correlated electrogoniometers with motion capture data for dance movements (Bronner & Agrahahsamakulsam 2006, Bronner *et al.* 2006). Correlation was possibly lower in the inversion/eversion axis due to the smaller range of motion and thus decreased signal to noise ratio when factoring measurement errors. Gait speed (i.e. walking vs. running) affected correlations both by reducing the R^2 value and also increasing the variance of the signal. This could be a result of increased marker 'wobble' from skin motion and soft tissue deformation during the higher impact events of running. There is also a potential for 'ghosting' of markers which would occur when the shutter speed of the motion capture system is not fast enough to capture an accurate circle.

Correlation between the electrogoniometer and Vicon® Plug-In Gait/OLGA model was lower than the electrogoniometer and triads. This was expected, as it is a modelled angle which operates on a skewed axis.

Correlations were still high ($R^2 > 0.69$), though closer analysis of discrete points will reveal several differences.

4.2.2 Discrete Point Analysis

4.2.2.1 Electrogoniometer compared to Motion Capture Triads

The analysis of measurement values during critical points of the gait cycle revealed significant differences at several places for walking (DF2, PF2, IN1 and IN2) and running (PF1 and IN2). The differences were however all below 2.2° which is within the error measurements recorded from the static testing. Thus, though significant differences between means may exist, they are within the expected error measurement of the devices.

4.2.2.2 Electrogoniometer compared to Vicon® Plug-In Gait/OLGA

Nearly every discrete measure analysed was statistically different for the comparison of electrogoniometer measurements to the Plug-In Gait model. This was likely a combination of factors that could cause such differences. First, the model attempts to calculate joint centers, and rotation axes based on external markers on the skin. The foot in particular has only three markers (Heel, Lateral Malleolus, and Toe). This in effect

simplifies all the articulations of the foot to a single joint which they term the 'ankle'. Flexion of the tarsal and metatarsal joints would be interpreted by the model as additional flexion of the ankle joint, thus the results are augmented relative to the rearfoot measures. This would be true for both plantar/dorsi flexion and inversion/eversion movements. In addition to simplifying the foot, The Plug-In Gait model attempts to find a rotated ankle axes using its built in algorithms. First an estimated knee joint axis is calculated based on femur rotation calculated from a single thigh marker (See calculations, Appendix I). The rotated knee axis is then translated to the ankle joint, where it is modified by a tibial torsion offset (estimated by a single wand marker on the lower leg). Since the ankle axis is dependent on the knee axis it is critical that the thigh and leg markers are placed as accurately as possible. The modeled ankle angles using Vicon Plug-In Gait were very different from the other two measurement methods (Figure 10) likely as a result of this model's estimated rotation of the ankle joint axes and also the augmentation of measurements due to movement in other joints of the foot contributing to what is referred to as the ankle in the model.

4.2 Conclusion

Given the favourable correlations between the elgon and triad methods as well as the low level of mean error, the electrogoniometer is comparable to the motion capture system when using triads to define fixed segments.

The outputs from the modeled Vicon Plug-In Gait/OLGA method, are not comparable to the outputs from the electrogoniometer mounted at the rear foot. Arguably, researchers and clinicians can thus have confidence in using elgons as an alternative assessment tool for ankle joint complex movements.

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APPENDIX

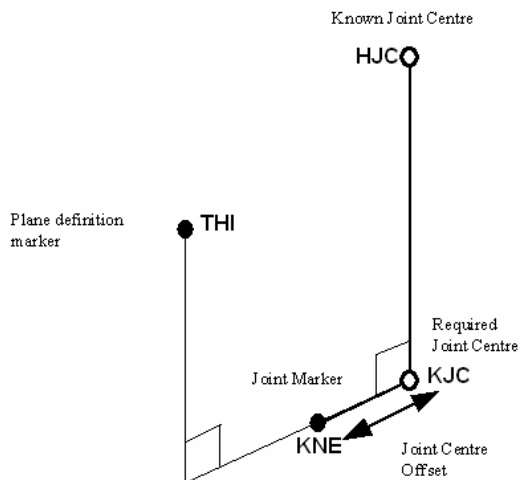
Appendix I – Plug-In Gait Model Calculations

Hip Joint Center:

- InterAsis distance = average distance between LASI and RASI throughout trial
- Asis-Greater Trocantor Distance= $0.1288 * \text{LegLength} - 48.46$
- $C = \text{MeanLegLength} * 0.115 - 15.3$
- $mr = \text{Marker radius (14mm)}$
- $aa = \text{InterAsis} / 2 + mr$
- Offset Vector X,Y,Z=
 - o $X = C * \cos(0.5\text{rad}) * \sin(0.314\text{rad}) - (\text{ASISTrocDist} + mr) * \cos(0.5\text{rad})$
 - o $Y = -(C * \sin(0.5) - aa \text{ (Left) (Negate for Right Hip)})$
 - o $Z = -C * \cos(0.5) * \cos(0.314) - (\text{ASISTrocDist} + mr) * \sin(0.314)$

Knee Joint Center:

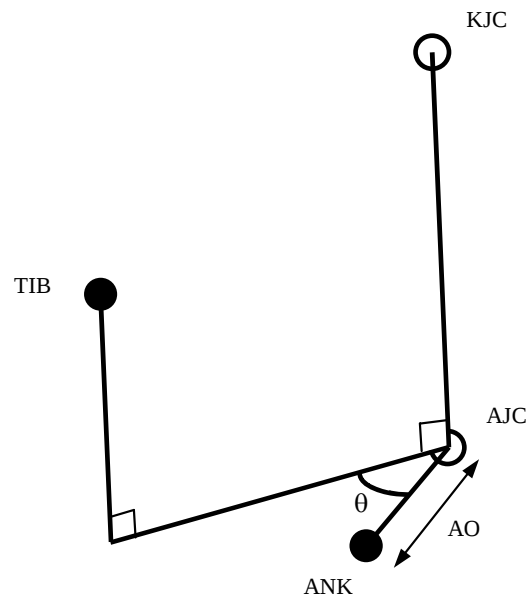
A 'Chord' function is used to calculate knee joint center. Three points are used to define a plane in which the joint center will lie. The points (HJC, THI, and KNEE) are used to calculate the knee joint centers.



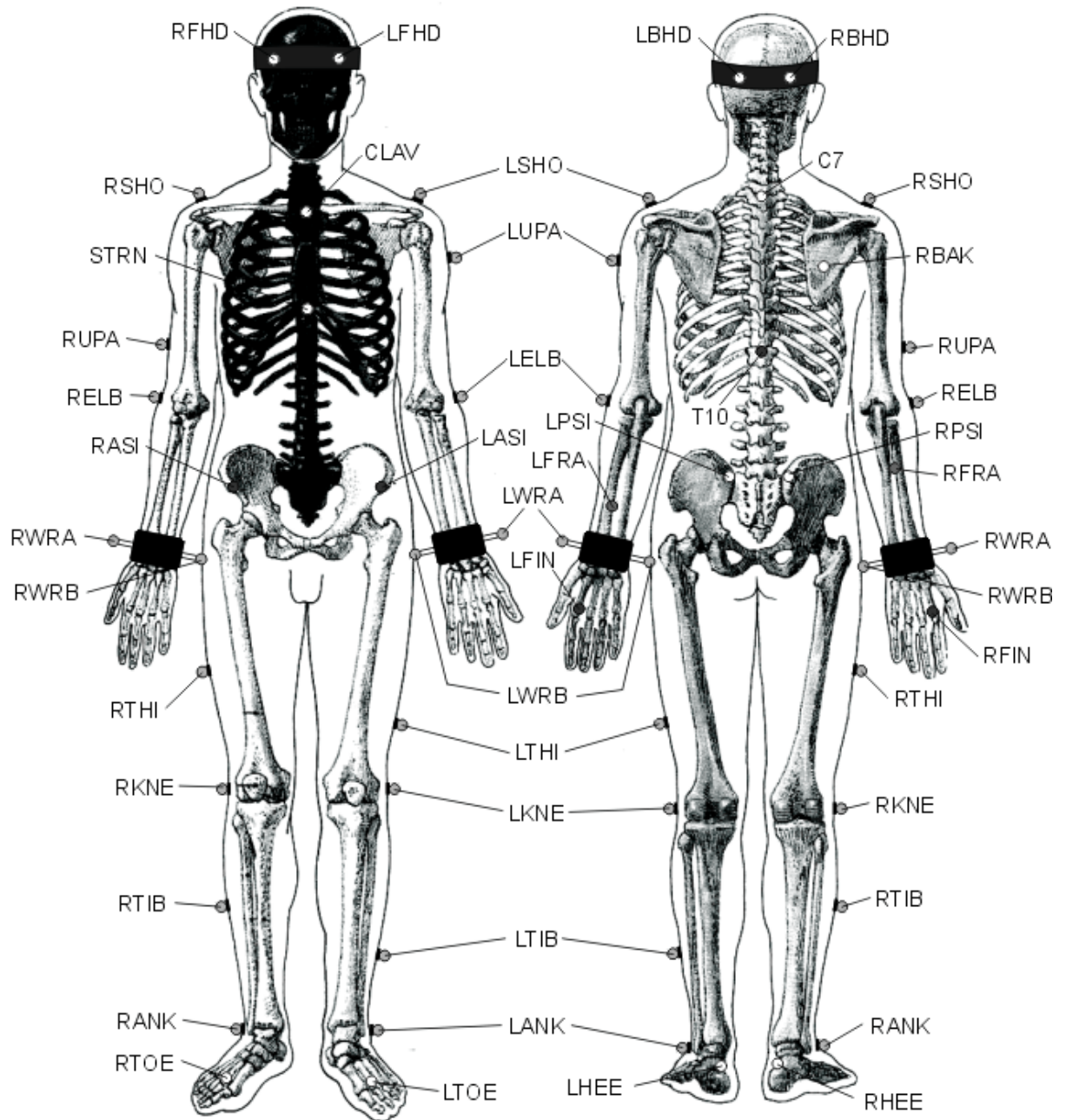
- KJC is translated by a joint centre offset perpendicular to the line of HJC-KJC in the direction determined by the A-P position of the THI wand marker.
- Joint Center Offset = $\frac{1}{2}$ knee width + marker radius from KNE marker

Ankle Joint Center

- Calculated using chord function explained above but using KJC-TIB-ANK markers.
 - Joint center offset (AO) = $\frac{1}{2}$ ankle width + mr from ANK marker
 - Angle between [KJC-AJC-ANK] plane and [KJC-AJC-TIB] Plane = Tibial rotation offset
 - Tibial rotation offset = Rotation of ankle axis relative to knee axis
- (Automatically calculated in Plug-In Gait Model during standing trial)



Appendix II – Plug-In Gait Marker Placement

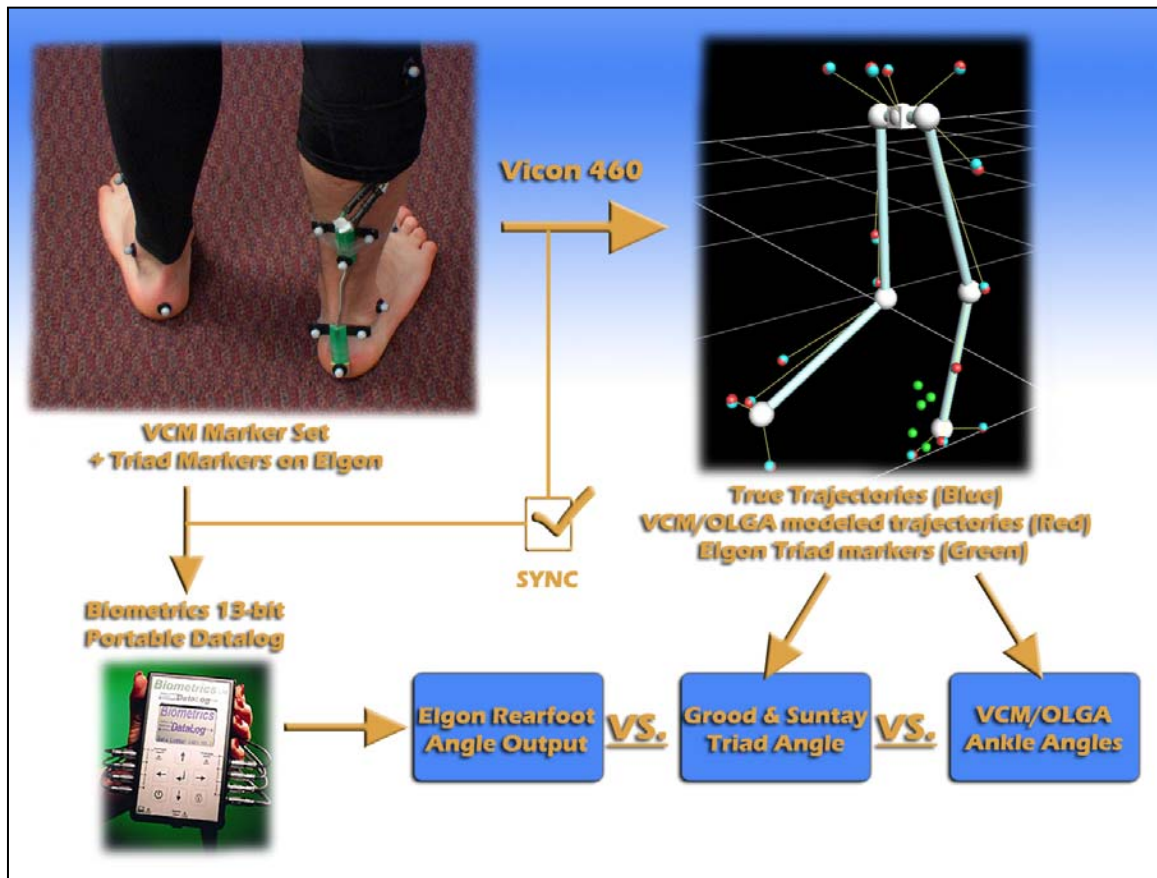


Reflective marker placement for Vicon® Plug-In Gait model for Workstation software.

Only lower body markers

(LASI,RASI,LPSI,RPSI,RTHI,LTHI,LKNE,RKNE,RTIB,LTIN,RANK,LANK,LHEE, RHEE,LTOE,RTOE) are used in the lower limb gait analysis.

Appendix III - Methodology Map



Appendix IV – Subject Forms and Ethics

IV.I Subject Information Form

Comparing flexible electrogoniometers to a 3D optical tracking system for measurements of ankle angles during walking and running.

Principal investigator: Ryan Ouckama (M.Sc Candidate)

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Montreal, Québec, Canada

Telephone: (514) 398-4184 x0583 email: ryan.ouckama@mail.mcgill.ca

Supervisor: Dr. David J. Pearsall email: david.pearsall@mcgill.ca

Location: McGill University

Introduction

Several devices are commercially available to quantify human joint motion from one to three dimensions. As with most electronic devices, with improved accuracy and reliability comes a significant increase in investment. A “gold standard” system in analysis of human movement, the Vicon® motion analysis system, requires substantial investment beyond that of many independent researchers and clinicians. Most manufacturers will provide an expected measurement error for their product. However, the methods for testing for these errors often are not standardized. If we compare alternative devices that measure joint angles, such as electrogoniometers, directly with the Vicon® system, the relative error could be reported to validate their use in research settings.

Purpose of the Study

The study you have volunteered for aims to validate an electronic device to measure joint angles, an electrogoniometer, by comparison to a very accurate 3D optical tracking system.

Your Participation Involves:

1. Providing informed consent prior to the experimental session
2. Completing a brief medical history questionnaire
3. Performing the following tasks during the session
 - a. An electrogoniometer will be secured to the rear of your ankle using 3M surgical tape and adhesive Tuff-Skin spray
 - b. Perform a 30s static standing trial
 - c. Perform five walking trials (10m)
 - d. Perform five jogging trials (10m)
 - e. During the trials a fanny pack will be secured around your waist containing a data collection device
4. Total collection should take no more than 60 minutes

Video Taping

The Vicon® system uses 6 digital video cameras to calculate three dimensional coordinates from raw video data. These cameras will be focused on your lower legs. These are not traditional video cameras and only record reflections from special markers. No identifiable video is recorded within this system, only three dimensional point locations.

Privacy and Confidentiality

In accordance to research standards at McGill University your name will be recorded. Subject names will **never** be published or released to unauthorized personnel. To protect your name in the case of publication, it will be substituted by a random number. The list of subject names and number assignments will be kept locked in the biomechanics lab in the Department of Kinesiology at McGill University. Only the principal investigator and his supervisor will have

access to this list. Computer data will be stored off-line, and then recorded to CD following completion of the study. This CD will be kept locked separate to the names list.

Benefits

No personal benefits will arise from your participation in this study. The information obtained from your participation may help to increase the use of electrogoniometers as valid measurement devices in published research and health related fields.

Foreseeable Discomfort

You will need to allow the principal investigator to palpate your ankle for anatomical features to ensure proper placement of the electrogoniometer. If you are uncomfortable either exposing your bare foot or having someone touch your feet, we would ask you withdraw from the study. 3M surgical tape is designed to be used directly on the skin. However, there is a small population that is sensitive to the adhesive used in this tape causing redness and slight swelling at the area.

Potential Risks

There are minimal risks associated with this study. The Vicon® system (<http://www.vicon.com>) utilizes near-infrared light and the manufacturer suggests not staring directly at the LED light sources around the cameras. The Vicon® system is widely used across the world in thousands of labs, hospitals, and animation studios to analyze human motion. Near-infrared light means that most of the light emitted is in the red spectrum with a small amount beyond the spectrum visible to the human eye. The non-visible spectrum poses no more risk than regular visible light.

Since you can not see some of the light in near-infrared spectrum it is potentially easier to stare directly at the lights for longer periods of time than a pure visible spectrum lamp. In this study all lamps will be at waist level facing downward toward the ankle joint, thus it is unlikely you will ever look directly at any lamp.

Subject Rights

Your participation is voluntary. You have the choice to withdraw from the study at any point of testing or withdraw your data following testing. You are also free to ask any questions to the experimenter at any time.

Contacts

In the event of adverse effects or if you need addition information you can contact:

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IV.II Subject Consent Form

Subject Statement:

I willingly choose to participate in the research study outlined above about testing joint angles using electrogoniometers and the Vicon system. I have received and read a detailed description of the experimental protocol. I am fully satisfied with the explanations that were given to me regarding the nature of this research project including the potential risks and discomforts related to my participation. I have acknowledged that my name will not be released or published in any way.

I am aware of my right to withdraw my consent and discontinue my participation at any time without any implications or prejudice.

Subject Signature:

Date:

Principal Investigator Statement:

I will ensure that this project is conducted in accordance with the policies and procedures governing the ethical conduct of research involving human subjects at McGill University.

Principal Investigator Signature:

Date:

IV.III Subject Medical Questionnaire

SUBJECT IDENTIFICATION

Name: _____ ID code: _____

Age: _____ years Sex: M or F

MEDICAL HISTORY

1. Have you ever been affected by lower leg joint disorders? Yes or No

If yes, specify _____

2. Have you recently complained of pain in the lower limbs, hips, or back? Yes or No

If yes, specify _____

3. Do you have any skin sensitivities or allergies, specifically to 3M medical adhesive tape? Yes or No

If yes, specify _____

IV.IV Institutional Ethics Approval Form



Faculty of Education – Ethics Review Board
McGill University
Faculty of Education
3700 McTavish; Room 230
Montreal H3A 1Y2

Tel: (514) 398-7039
Fax: (514) 398-1527
Ethics website: www.mcgill.ca/rgo/ethics/human

Faculty of Education – Review Ethics Board Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 639-0206

Project Title : *Comparing flexible electrogoniometers to a 3D optical tracking system for measurements of ankle angles during walking and running*

Applicant's Name: Ryan Ouckama Department: KPE

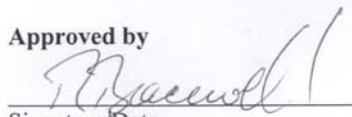
Status: Master's student Supervisor's Name: David Pearsall

Granting Agency and Title (if applicable): n/a

Type of Review: Expedited ☒ Full ☐

This project was reviewed by: Starke-Meyerring/Stringer

Approved by

 Mar 30, 2006

Signature/Date

Robert Bracewell, Ph.D.

Chair, Education Ethics Review Board

Approval Period: Mar 23/06 to Mar 23/07

All research involving human subjects requires review on an annual basis. An Annual Report/Request for Renewal form should be submitted at least one month before the above expiry date. If a project has been completed or terminated for any reason before the expiry date, a Final Report form must be submitted. Should any modification or other unanticipated development occur before the next required review, the REB must be informed and any modification can't be initiated until approval is received. This project was reviewed and approved in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Subjects and with the Tri-Council Policy Statement on the Ethical Conduct for Research Involving Human Subjects.

3/30/06

Appendix V - Subject Anthropometric Measures

Subject (Sex)	Age (Yrs)	Mass (Kg)	Height (cm)	Leg Length ¹ (cm) L/R	Knee Width ² (cm) L/R	IMD ³ (cm) L/R
1 (F)	20	53	169	89/89	9.3/9.3	6.6/6.6
2 (M)	25	74	184	94/93	10.0/10.0	7.3/7.7
3 (F)	24	59	172	90/90	9.2/9.0	6.7/6.8
4 (F)	21	64	157	80/81	10.4/10.2	6.5/6.5
5 (M)	24	82	186	95/96	10.6/10.6	8.0/7.9
6 (M)	54	80	173	92/91	9.7/9.7	7.7/7.8
7 (M) **	30	61	168	89/88	9.1/8.9	6.8/6.8
8 (M)	41	67	171	87/86	9.7/9.7	7.7/7.6
9 (M)	20	94	181	91/90	10.0/9.9	8.0/7.9
10 (F)	19	65	161	83/84	10.0/10.0	6.5/6.3
Mean(SD)	27.6(11.9)	70.9(12.8)	172.7(9.8)	89.0(4.9)/ 88.9(4.6)	9.9(0.5)/ 9.8(0.5)	7.2(0.6)/ 7.2(0.7)

¹ Measured between the ASIS of ilium and the medial malleolus while standing.

² The medio-lateral width of the knee across the estimated line of the knee axis.

Measured while standing.

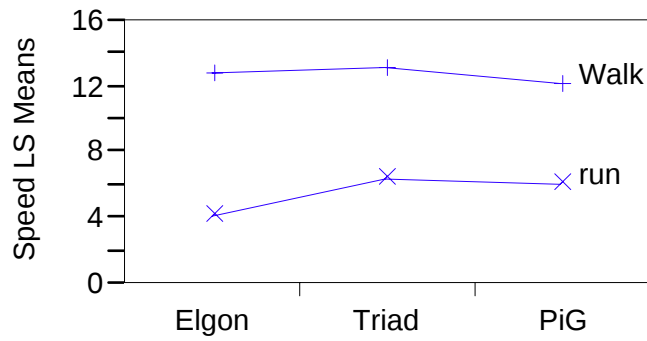
³ Inter-Malleolar distance. Medio-lateral distance across the malleoli of the ankle measured while standing.

* Significant digits change for the last two columns as a more precise caliper was used versus a flexible tape for the larger measures.

** This subject was excluded from analysis due to poor adherence of markers during the 3D capture and loss of critical markers as a result. Values do not contribute to the reported means.

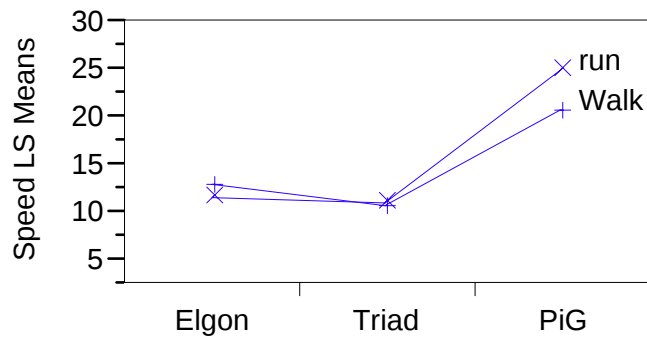
Appendix VI - Least-Square Mean Plots across device and Speed

PF1



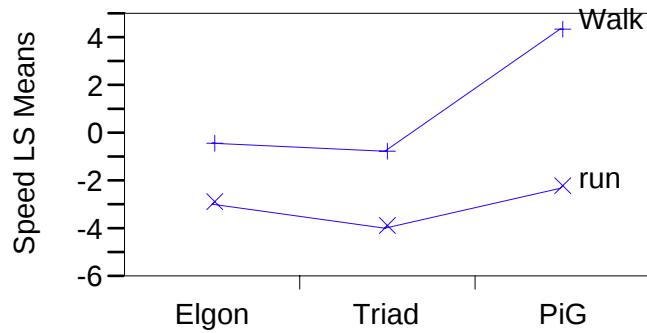
Speed	Elgon	Triad	PiG
Walk	12.7944387	13.1859496	12.1873665
run	4.15538176	6.31863385	6.11679656

PF2



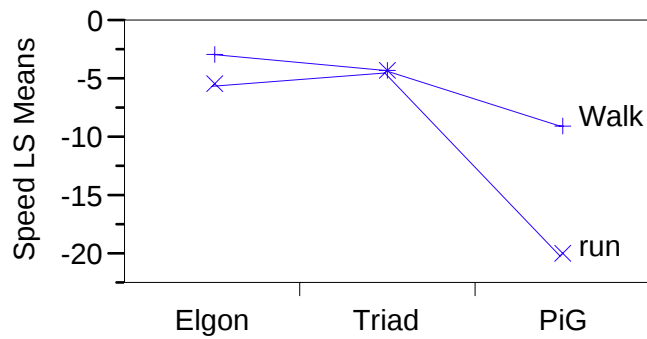
Speed	Elgon	Triad	PiG
Walk	12.9601056	10.8282619	20.802311
run	11.6426476	10.9559814	24.7550932

DF1



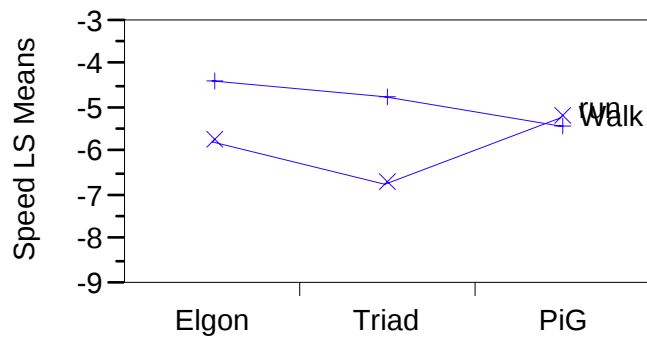
Speed	Elgon	Triad	PiG
Walk	-0.3597883	-0.6883173	4.34948876
run	-2.9361887	-3.8966308	-2.3001401

DF2



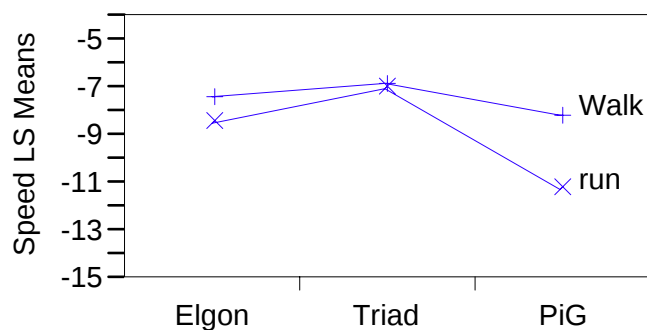
Speed	Elgon	Triad	PiG
Walk	-2.8965247	-4.1057922	-9.0121335
run	-5.5481569	-4.4395979	-20.055185

IN1



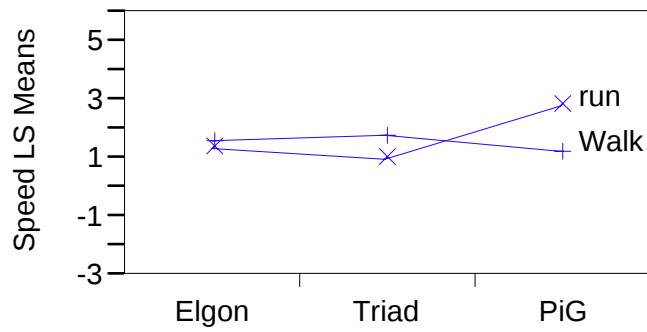
Speed	Elgon	Triad	PiG
Walk	-4.3502278	-4.7465855	-5.4175409
run	-5.7767507	-6.7399336	-5.2290654

IN2



Speed	Elgon	Triad	PiG
Walk	-7.3926375	-6.791564	-8.1744242
run	-8.5541496	-7.0745733	-11.239319

EV1



Speed	Elgon	Triad	PiG
Walk	1.56947121	1.80369069	1.24073134
run	1.3424493	0.94908459	2.80341458