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15 MOTION ANALYSIS STRATEGY APPROPRIATE FOR 3D KINEMATIC ASSESSMENT OF CHILDREN AND ADULTS WITH OSTEOGENESIS IMPERFECTA

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INTRODUCTION

Human motion analysis provides a quantitative means of assessing whole body and segmental motion of subjects with musculoskeletal pathologies. This chapter describes a low cost motion analysis appropriate for complete three-dimensional (3D) assessment of upper and lower extremity kinematics. The system has been designed to support lower cost outreach efforts that require accuracy and resolution on the order of classical fixed lot systems such as Vicon. The focus of this work addresses the assessment needs typically seen in adults and children with osteogenesis imperfect (OI) experiencing ambulatory and upper extremity challenges.

Fundamental Approach

The general method used for quantitative motion assessment defines a segmental model of the skeletal region of interest with intersegmental joints. Quantitative description of the tri-axial joint motion requires a mathematical model of the system and a series of external markers that are visible to the

motion capture system and in proximity to key anatomical landmarks. An example would be the Helen-Hayes marker set where the body is broken up into seven segments; three segments for each leg as well as a segment describing the pelvis.[1] Each segment is created by three or more markers to define a plane such that tri-axial rotation is fully defined. The preference is to employ a Cartesian coordinate system embedded into each body segment for calculation of intersegmental joint angles. Optical cameras are widely used to record the position of the external markers in space as the subject ambulates through a predetermined capture volume. At least two cameras must simultaneously view each marker in order to determine its 3D coordinates. Most systems are redundant with multiple cameras because some markers can be obstructed from the view of cameras during arm swing and with the use of assistive devices, such as Lofstrand crutches and walkers. All cameras are synchronized to record marker position at the same time using a frame rate typically between 50 and 250 frames per second depending on the application. Once the marker positions have been located in 3D space, associated labels are applied to each marker to define anatomic location, i.e. RASIS: Right Anterior Superior Iliac Spine.

Biomechanical modeling software is then used to determine joint orientation and motion between segments. In lower extremity gait analysis, this would include motion at the pelvis, hip, knee, and ankle in all three anatomic planes. The analytical software usually incorporates algorithms and filters to better estimate joint orientation, angular velocity, and angular acceleration.[1]

Typical Applications

Motion analysis systems have been used in the clinical setting for pre- and post-treatment assessment of subjects with upper and lower extremity pathologies. Almost any pathology affecting the musculoskeletal system can be assessed using motion analysis. Depending on the area of focus for a particular patient, motion analysis can be used to describe broad motion such as hip, knee, and ankle or can be more specific when looking at motion of the hindfoot, midfoot, and hallux.[3-11] This can be similarly done when examining the upper extremities while trying to focus on motion at the torso, shoulder, elbow, and wrist.[12-15] With the ability to assess both upper and lower extremities using motion analysis, disabilities can be described within all three anatomic planes of motion that may have been more difficult to assess previously by observation only.

Osteogenesis imperfecta (OI) is a pathology that has received more recent attention within the motion analysis community. A study by Graf et al. compared gait characteristics in children with type 1 OI to those of age-matched controls. The results from the study showed that the OI group demonstrated increased double limb support, delayed foot off, and decreased ankle range of motion and plantar flexion during the third rocker.[16] Joint angle characteristics between controls and subjects with OI are shown in Figure 1. One specific aim of this study was to assess push-off power at the ankle during gait. The study found that, due to weaker plantar flexors, the children with OI had a reduced ankle power production and decreased ankle angle velocity in the sagittal plane.[17] The authors noted that results could be used to gain a better understanding of OI and to help improve treatment planning and overall quality of life.

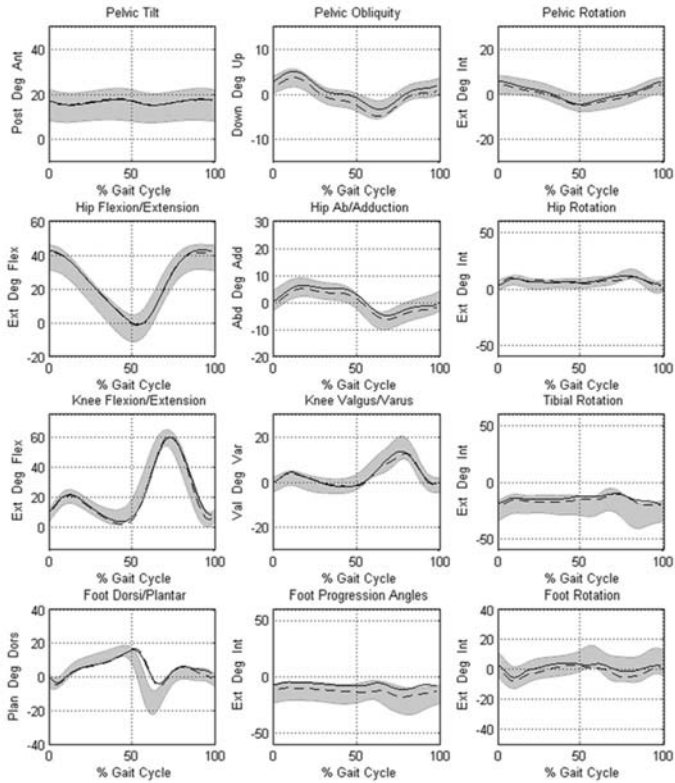

Figure 1. Joint kinematic comparison between normal and OI populations. The band represents the average of the normal population and the solid and dashed lines represent the average left and right sides of the OI population, respectively.

Kinetics has also been incorporated into assessment of persons with OI. A study by Fritz et al. quantified loading conditions at the femoral head and condyles along the femur. The authors wanted to determine the risk of femoral fracture for a subject with OI type I during normal ambulation. Findings included the OI modeled femur showing no risk of fracture during normal gait and that the highest stress level occurred during the mid-stance and loading response phases of gait.[13]

Motion Analysis Systems

There are a wide variety of motion analysis systems available on the market today. The most prevalent systems will be discussed here. Vicon (Vicon Motion Systems, Oxford, England) is one of the most traditional systems currently being used in the clinical setting. The system captures and tracks motion using passive markers, and offers standard components typically used by researchers or clinicians during gait analysis. The system utilizes Nexus software to record movement data along with synchronized signals from other measurement devices including EMG (electromyography) and force plates. Vicon Nexus offers several features to automate processing including automatic marker labeling and event detection (i.e. foot strike and foot off). Vicon's Polygon software allows post processing to display joint kinematics, kinetics, and EMG data.[18]

Another system is the Optotrak Certus (Northern Digital Inc, Ontario, Canada). Optotrak incorporates a "Smart Marker" system of active markers. Battery powered strobes eliminate the need for wires. Up to 50 strobes can be used at a time per battery system. The Optotrak software allows for incorporation of force plates, EMG, eye-trackers, and other third-party instrumentation. The Optotrak motion analysis system is compatible with other software including Visual3D (C-Motion, Germantown, MD), which is used for higher level data processing by multiple vendors.[19]

Motion Analysis Corporation (MAC) (Santa Rosa, CA) is another company that provides motion analysis systems used for gait analysis. Much like the Vicon system, MAC uses passive markers. The main motion capture software called Cortex is used for all phases of recording including calibration, tracking, and post processing. These systems also allow simultaneous analog data input from force plate and EMG sources. Cortex is used to calculate and display kinematic, kinetic, and EMG data. SIMM (MusculoGraphics, Inc., Santa Rosa, CA) is software supplied by MAC which is used for monitoring changes

in muscle length and muscle moment arms during gait.[20] This software can also be used with various gait analysis systems, including Vicon.

Systems can also be developed by combining hardware, data capture, and processing software. A recent development described here is a combination of Optitrack Cameras (NaturalPoint, Inc., Corvallis, OR) and Visual3D and AMASS (C-Motion Inc., Germantown, MD) software. The Optitrack cameras were originally designed to be used for video game motion analysis, but using them for clinical applications is also possible. The Optitrack hardware includes V100:R2 motion capture cameras that are much smaller than the standard Vicon or MAC cameras. The AMASS software is used for capturing and labeling marker data while Visual3D software is used for kinematic analysis and external signal synchrony (EMG, force plate).[21] Other cameras are also available from Naturalpoint, Inc. that can be incorporated with the C-motion, Inc. software. One in particular would be the Flex 13 cameras which are the same size as the V100:R2 cameras and only a few hundred dollars more but provide three times greater resolution than the V100:R2 cameras.

New Horizons in Motion Analysis Technology

Two independent factors to consider when developing a system are cost and performance. Listed below is a comparison of performance characteristics of all systems described herein (Table 1). The first three systems have been tested for accuracy, precision, and/or resolution.[22-24] Traditionally, motion analysis system cost can range from $50k - $300K, which may not be affordable for some clinics and hospitals, particularly those in underdeveloped countries. The combination of Optitrack cameras and C-motion software may provide a less expensive alternative with the hardware and software priced at less than $50K. The static and dynamic calibration of the cameras and kinematic comparison to Vicon will be discussed further with respect to its potential use for a less expensive, yet reliable, motion analysis system. If successful, this combination system will allow a broader population to undergo gait analysis and whose ability to ambulate could be greatly improved from the information surgeons and physicians obtain from these assessments. In particular, it can be applied to benefit children and adults with OI in clinics that could not otherwise afford motion analysis technology.

Table 1. Motion analysis system performance parameters.

	Markers	Sampling Rate (frames/sec)	System Resolution (mm)	Precision (mm)	System Accuracy (%)
Optitrack	Passive	50-100	0.63	-	94.82
Vicon	Passive	120-250	1.49	-	98.3
Optotrack	Active	50	-	0.03	98.44
Cortex (MAC)	Passive	200	-	-	-

METHODS

Instrumentation

An eight-camera Optitrack V100:R2 (Naturalpoint Inc., Corvallis, OR) motion capture system was used to acquire marker data at 100 frames per second (fps) with markers measuring 15.9 mm in diameter. ARENA motion capture software (Naturalpoint Inc., Corvallis, OR), which came with the Optitrack cameras, was used to acquire the 3D marker data. A Styrofoam cone was used for static testing while a combination of the Styrofoam cone and a bar were used for dynamic testing represented by Figure 2A and Figure 3A, respectively.

For angular dynamic testing, a Biodex System III (Biodex, Biodex Medical Systems, Shirley, NY) was employed to generate a constant angular velocity for a desired angular range. The Biodex system was used for angular dynamic testing since the system can be programmed to rotate in multiple planes.[22]

Kinematic joint angle data was obtained using ten Optitrack V100:R2 cameras in collaboration with AMASS and Visual3D software (C-Motion, Inc. Germantown, MD).

Camera Validation Protocol

Accuracy and resolution of the Optitrack motion capture system were determined statically and dynamically.[22,23,25,26] For static linear testing, three markers were placed on the Styrofoam cone at measured distances associated with typical foot marker placements (Figure 2A).[22,23] The short foot and long foot distances measured 57.5 mm and 140.6 mm, respectively. The short foot marker distance was selected as a representative constraint

for potential foot models. The Styrofoam cone was placed along the Cartesian coordinate axes and positioned to face the center of the capture volume at the five locations seen in Figure 2B. A 3-second trial was recorded at each of the five locations along all three primary axes. Marker data was processed by performing marker labeling and exported for statistical analysis in MATLAB.

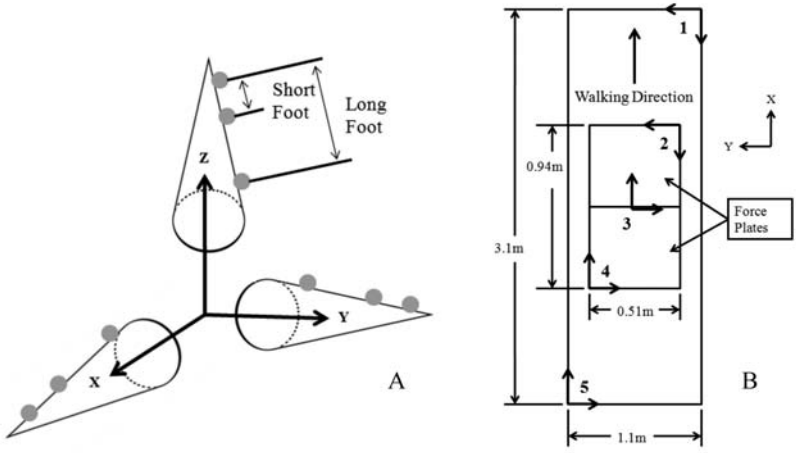

Figure 2. (A) Calibration cone used for static testing. (B) Locus for static calibration within capture volume.

For linear dynamic testing, the Styrofoam cone and leg bar were fixed to each other to represent a leg with typical marker placement used for whole body lower extremity gait (Figure 3A). Five markers were located on the leg bar at 205.3 mm, 417.8 mm, 181.6 mm, and 397.2 mm, representing the approximate distances for hip to mid-thigh, hip to knee, knee to mid-calf, and knee to ankle, respectively. These marker locations are also analogous to those used for upper extremity analysis (walker, crutch, cane, and wheelchair).[27] Marker distances used for the Styrofoam cone were identical to those of the static testing. The entire lower extremity system (foot and leg segment) was then translated at a free walking speed through the capture volume in the positive and negative X-direction five times.

Angular dynamic testing employed the Biodex System III to rotate through a range of 305 degrees. Five markers were placed on the Biodex attachment arm at distances of 57.5 mm, 140.6 mm, 205.3 mm, and 417.8 mm (Figure 3B). The marker distances were analogous to those used in the linear dynamic testing. The Biodex was programmed to rotate through a range of 305 degrees at 90 deg/sec. Data were recorded for five trials in all three

planes of motion (XY, YZ, XZ) during clockwise and counterclockwise rotation. A 2-second portion, in which the angular velocity was calculated to be constant, was used for analysis.

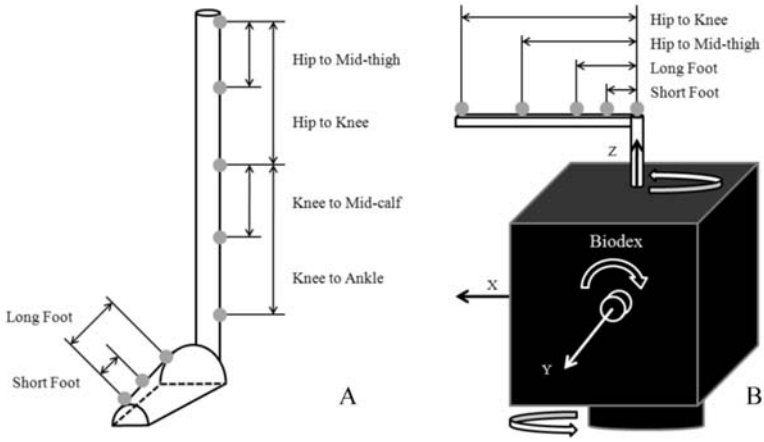

Figure 3. (A) Linear dynamic calibration frame. (B) Biodex with rotational dynamic calibration frame. Marker distances are representative of those used in human gait.

System resolution was calculated using the following equation:[22,23]

$$R = \left| D - \frac{1}{n}\sum_{i=0}^{n-1} d_i \right| \pm t\left(\frac{s}{\sqrt{n}} + \varepsilon_r + \varepsilon_m \right) \quad (1)$$

Where:

R	System resolution;
D	measured (empirical) distance;
n	total number of samples;
d_i	computed distance;
t	t-test coefficient [23];
s	sample standard deviation;
ε_r	round-off error = (5/10m);
ε_m	measurement error; based on micrometer resolution (±0.02 mm);
m	number of significant digits.

System accuracy was computed as:[22,23]

$$A = \left(1 - \frac{\left| x_w - \frac{1}{n} \sum_{i=0}^{n-1} d_i \right|}{\frac{1}{n} \sum_{i=0}^{n-1} d_i} \right) \times 100\% \qquad (2)$$

Where:

A	system accuracy as a percentage;
x_w	"worst" data point.

The average value of the computed distance was used as an estimate of the true distance between markers due to measurement error.[28]

Joint Kinematics

Kinematic joint angle data was obtained by applying 15 reflective markers (diameter = 14mm) along with knee alignment devices (KAD's) on 10 control patients with normal gait. Markers were placed such that the pelvis, thighs, shanks, and feet were represented by a plane made up of three markers. The pelvis was represented by markers located on the left and right ASIS as well as a sacral marker. The thigh was represented by an ASIS marker, thigh wand, and knee marker located on the lateral femoral epicondyle. The shank was represented by the knee marker, shank wand, and lateral malleolus marker. The foot was represented by the lateral malleolus, heel and toe marker located on the head of the 2nd metatarsal. The KAD's were used only during the static trial to more accurately describe the joint center of the knee. A series of required measurements were also taken including height, weight, inter-ASIS, ASIS to lateral malleolus, thigh radius, knee width, and ankle width.

Each subject stood still in the center of the capture volume for a static capture trial. For dynamic capture trials, the subject stood at one end of the capture volume and proceeded to ambulate across the volume at a free walking pace to the other end. Data were recorded at a rate of 100 fps. Ten-second trials were used to ensure sufficient time for the subject to ambulate across the capture volume within the designated time frame. A total of twelve trials were recorded where the subject started walking with their left foot for the first six trials, and started walking with their right foot for the second six trials. Three trials for each side of the body where chosen in which there was

the least amount of marker drop out. Using AMASS, the trials were then labeled and exported to c3d files for processing in Visual3D.

Visual3D software was then used for kinematic analysis. The static trial was used to apply the Helen-Hayes marker set model with KAD's.[1] This model is based off the plug-in-gait model used by Vicon, a clinical standard. Segments including a pelvis, thigh, shank, and foot were created with intersegmental joints to describe joint kinematics. Each segment is given a local coordinate system to help describe motion of that particular segment. To describe the joint kinematics at the hip, a segment is described with respect to a reference segment. In this case it would be the thigh segment coordinate system moving with respect to the pelvic coordinate system. This same process is performed for the knee, and ankle. Pelvic motion is described as the pelvis coordinate system moving with respect to the global coordinate system. Once the model was applied, the dynamic trials were implemented into Visual3D for processing. For each dynamic trial, foot strike and foot off were determined. The frame at which the heel marker no longer moved forward was deemed as foot strike and the frame at which the metatarsal marker initiated forward movement was deemed as foot off.

The joint angle data can then be plotted within Visual3D. The data was interpolated with a maximum gap of 10 frames using a 3rd order polynomial. Visual3D uses a Segmental Optimization or Global Optimization to interpolate gaps in the data due to marker drop out.[29,30] In addition, the data was filtered using a 6 Hz Butterworth filter.

The marker data collected in AMASS was also processed using Vicon's Nexus software. The "KAD PlugInGait (SACR)" model was attached to the marker data collected from AMASS. This model is the standard model for lower extremity kinematic analysis during gait when using Vicon. Each dynamic trial associated with each subject's static trial was opened and labeled. Foot strike and foot off were determined for each dynamic trial. In a similar fashion to Visual3D, foot strike was determined by looking at when the forward motion of the heel marker stopped, and foot off was determined by looking at when forward motion began for the 2nd metatarsal marker. Marker gaps were filled using direct pose estimation or global optimization.[29,30] A Woltring filter with a mean squared error of 10 was applied to the data. The dynamic model was then run to calculate the joint angle data for the pelvis, hip, knee, and ankle.

Statistics

For statistical analysis, a variance components model was used to compare the data between Visual3D and Nexus.[31,32] The joint angle values computed from Visual3D and Nexus include the maximum, minimum, and range values for the pelvis, hip, knee, and ankle in all three anatomic planes of motion. In addition, cadence, walking speed, step length, and stride length were compared. The model assumes four different sources of variability including the subject, side of the foot (left or right), which system was used to calculate the joint angles, and all other possible sources of variability aggregated in the error term. The main interest was to see if a system change, Visual3D or Nexus, showed a significant contribution to the total variability of the joint angle data. In addition, a paired t-test was used to compare the mean values from all of the subjects between the two systems. The associated p-values and confidence interval were determined when the two systems were compared. A p-value of 0.01 was used to determine significance in the variance components model and paired t-test.

RESULTS

Static and Dynamic Testing

The maximum and minimum accuracy and resolution values for the static and dynamic testing are shown in Table 2. The minimum accuracy for static testing was 99.31% for the short foot distance along the X-axis and the maximum accuracy was 99.90% for the long foot distance along the Z-axis. The minimum resolution for static testing was 0.63±0.15 mm for the long foot distance along the Y-axis and the maximum resolution was 0.04±0.15 mm for the short foot distance along the Z-axis.

The minimum accuracy for linear dynamic testing was 95.59% for the short foot distance going forward (+X direction) through the capture volume and the maximum accuracy was 99.77% for the knee to mid-calf distance going forward (+X direction) through the capture volume. The minimum resolution for linear dynamic testing was 0.37±0.23 mm for long foot distance walking in the –X-direction though the capture volume and the maximum resolution was 0.09±0.26 mm for the knee to ankle distance walking in the –X-direction through the capture volume.

The minimum accuracy for angular dynamic testing was 94.82% for the short foot distance along the XY-plane and the maximum accuracy was 99.68% for

the hip to knee distance along the XZ-plane. The minimum resolution was 0.61±0.31 mm for the hip to knee distance along the YZ-plane and the maximum resolution was 0.10±0.19 mm for the long foot distance along the XZ-plane. All of the resolution values are at the 0.05 level of significance.

Table 2. Maximum and minimum accuracy and resolution values for three different calibration methods.

Test Method	Maximum Accuracy (%)	Minimum Accuracy (%)	Maximum Resolution (mm)	Minimum Resolution (mm)
Static	99.90	99.31	0.04 ± 0.15	0.63 ± 0.15
Linear Dynamic	99.77	95.59	0.09 ± 0.26	0.37 ± 0.23
Angular Dynamic	99.68	94.82	0.10 ± 0.19	0.61 ± 0.31

Temporal Parameters and Joint Kinematics

The joint angle comparison between Visual3D and Nexus is shown in Figure 4. The solid line with the darker band represents the joint angle data provided by Visual3D and the dashed line with the lighter band represents the joint angle data calculated from Nexus. The plots display the mean from all subjects and one standard deviation for the joint angle with respect to percent gait cycle. This data represents the joint angles calculated for the right side of the body. The left side was compared in a similar fashion. When assessing both sides, no significant difference was seen between the two sets of data from Visual3D and Nexus except for tibial torsion as well as all of the data for the foot segment movement. Table 3 shows the maximum, minimum, and range of tibial torsion and foot kinematics that that showed significant difference when analyzed statistically. All of the temporal and stride parameters including step length, stride length, cadence, and walking speed showed no significant difference between systems. Visual3D calculated values of 112.42 steps/min, 1.200 m/s, 0.637 m, and 1.281 m for cadence, walking speed, step length, and stride length, respectively. Nexus calculated values of 112.73 steps/min, 1.198 m/s, 0.637 m, and 1.278 m for cadence, walking speed, step length, and stride length, respectively.

Table 3. Representation of maximum, minimum, and range values associated with joint angles where significant differences were seen.

	Maximum		Minimum		Range	
	Visual3D	Nexus	Visual3D	Nexus	Visual3D	Nexus
Right Tibial Rotation	18.13	14.56				
Left Tibial Rotation	13.37	11.25				
Right Foot Dorsi Plantar	14.92	15.3	-8.78	-12.9	23.71	28.21
Left Foot Dorsi Plantar	13.85	14.99	-11.64	-15.41	25.49	30.4
Right Foot Progression	-5.16	-1.72	-13.51	-11.43	8.36	9.72
Left Foot Progression	-2.74	-0.66	-11.48	-9.88	8.75	9.22
Right Foot Rotation	-11.31	-6.08	-24.78	-18.69		
Left Foot Rotation	-6.22	-0.57	-18.55	-16.55		

DISCUSSION

System Characterization

The static and dynamic calibration done to the V100:R2 cameras provides comparable results to studies reported by Kidder et al. and Myers et al. Kidder used a five camera Vicon motion tracking system. Static results showed a minimum accuracy of 99.4% and resolution of 0.6 ± 0.82 mm at the 0.05 level of significance. Dynamic results showed a minimum accuracy of 98.3% and resolution of 1.49 ± 0.1 mm at the 0.05 level of significance [23]. Myers used a fifteen-camera Vicon 524 motion tracking system. Static results showed a minimum accuracy of 99.88% and a resolution of 0.60 ± 0.14 mm at the 0.05 level of significance. Dynamic results showed a minimum accuracy of 99.18% and resolution of 2.96 ± 3.53 mm at the 0.05 level of significance [22]. The Optitrack cameras provided comparable results to those seen in the Kidder and Myers studies with a minimum static accuracy of 99.31% and resolution of 0.63 ± 0.15 mm at the 0.05 level of significance, and dynamic accuracy of 94.82% and resolution of 0.61 ± 0.31 mm at the 0.05 level of significance.

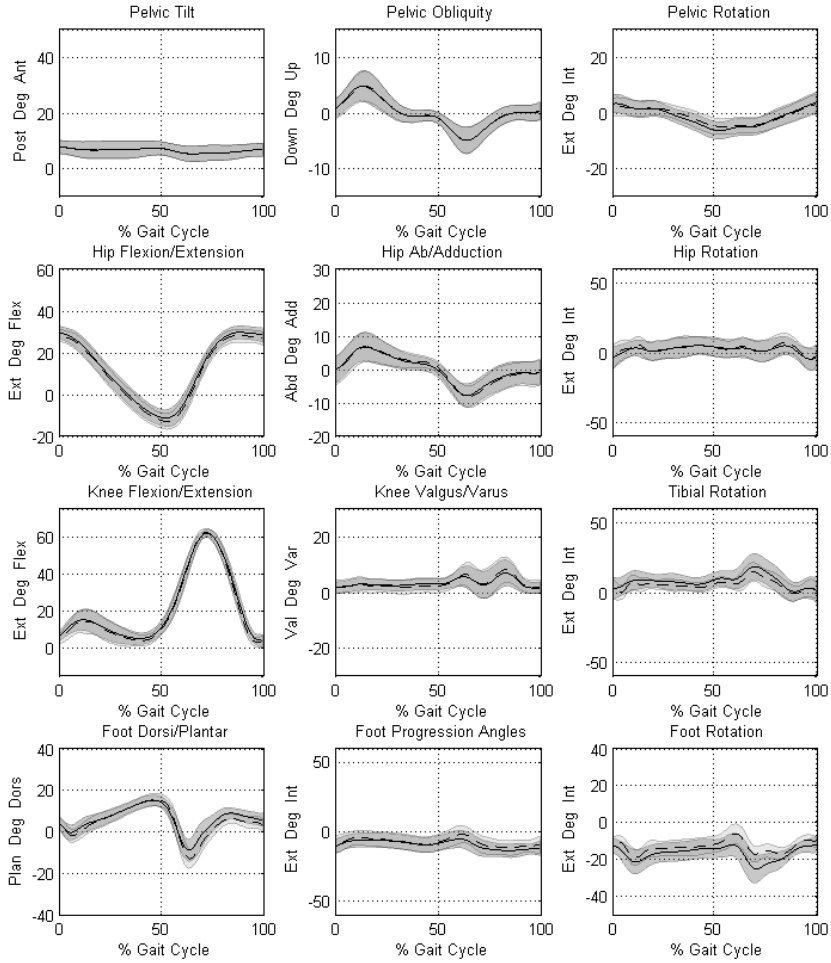

Figure 4. Joint angle kinematics for right side of body compared between Visual3D and Nexus. Visual3D is represented by a solid line and darker standard deviation band. Nexus is represented by a dashed line and lighter standard deviation band. Because there was significant overlap between the two data sets, some graphs may appear as one set of data when in fact there are two.

These values show that the V100:R2 Optitrack camera system can provide as accurate 3D marker data as that of current clinical standards at a fraction of the cost. The marker position data is essential in providing accurate motion analysis results. Any subtle deviation in the marker position data can result in a larger deviation when calculating joint angles. A study by Stagni et al. found that when trying to calculate hip joint centers, a mislocation of 30 mm of the marker placement resulted in an error of 22% in the hip flexion/extension moment.[33] Several other factors can play into the accuracy

of marker position data such as camera position, what view each camera has on the markers, pixel value, and number of cameras. With the advancement of technology and cost of equipment decreasing, the ability to collect accurate and reliable data at a cheaper price is becoming more of a reality.[36]

Kinematic and Temporal Findings

The lower cost system provides comparable results to that of clinically standard systems like Vicon. This can be seen in the temporal and stride parameters as well as the joint kinematic maximum, minimum, and range values for the pelvis, hip, knee, and ankle. No significant differences were seen in the three anatomic planes at the pelvis, hip, and knee with the exception of the maximum tibial rotation angle. Primary differences were found, however, at the ankle due to variations in the foot segment coordinate system with each model (Visual3D and Nexus). Temporal and stride parameters, including cadence, walking speed, stride length, and step length, showed no significant differences between the two systems.

Depending upon the similarity of applications, users should also be aware of more subtle differences in estimation algorithms and filtering.[34] Estimation algorithms are used to fill gaps from marker drop out while filters are set typically to reduce higher frequency noise and artifact signals.[29,30]

With the lower cost system, more hospitals and clinics can offer motion analysis services in the hope that more people can benefit from this technology including those in underserved areas.

Future Applications

With the cameras and biomechanical modeling software validated, several directions can be taken to expand the low cost system. Advancements in technology will allow cameras with increased resolution and accuracy to be used in replacement of the cameras validated in this chapter. The improved cameras will more closely approximate the system requirements of more expensive equipment. Recent hardware developments will also allow the integration of force plates and EMG systems. This will allow more complete characterization of mobility including full joint dynamics and muscle activity.

Access to this technology can now be offered to new populations of children and young adults with mobility challenges. New biomechanical models can be developed to assist these populations by analyzing upper extremity

pathologies, assisted mobility, and segmental distal extremity motion. The combined advances in technology and population outreach efforts will serve to significantly increase access to quantitative mobility assessment for those with musculoskeletal pathologies. This access will simultaneously offer new opportunities to clinicians and researchers interested in mobility assessment and improved patient care. The complex mobility needs of children and young adults with OI, and particularly those in underserved areas, can benefit significantly from these advances.

CONCLUSION

The Optitrack motion capture system was evaluated through static, linear dynamic, and angular dynamic trials. Joint angle data were compared between a standard Vicon system with Nexus software and the lower cost Optitrack system with C-motion software (AMASS and Visual3D). Joint angle maximum, minimum, and range values are not significantly different at the pelvis, hip, and knee, expect for the maximum angle of tibial rotation. There were significant differences due to system (model) variability for the ankle. This can be explained because of the variance in coordinate systems used for the foot segment in the two systems. Validation of the low cost system is a first step towards expansion of motion analysis to a broader clinical community, particularly those with OI and disabilities that restrict patients to a wheelchair or other assistive devices. Kinetic application will require further incorporation of force plates and EMG data. Lower cost system availability will increase opportunities for researchers and clinicians as they examine an ever increasing range of mobility challenges to persons with disabilities including OI.

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