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Detecting Anatomical Leg Length Discrepancy Using the Plug-in-Gait Model

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Abstract: Leg length discrepancy (LLD) is a significant factor influencing several pathological conditions. Gait analysis is based on biomechanical gait models calculating joint kinematics; however, no previous study has validated its ability to detect anatomical LLD. The aim of the present study was to compare the validity of the Vicon® Plug-in-Gait-model (PGM) in measuring femur and tibia segmental length discrepancy with measurements attained by X-ray. Fifteen participants with suspected leg length discrepancies underwent a lower limb X-ray and a standing calibration trial using a motion analysis system (Vicon®, Oxford Metrics, UK). Femur and tibia segment lengths were deducted from both measurements. No differences were found when measuring the discrepancies between sides for the femur ($p = 0.3$) and tibia ($p = 0.45$) segmental length. A high correlation was found between methods (r = 0.808–0.962, $p < 0.001$), however, a significant difference was observed when measuring the femur and tibia length ($p < 0.0001$). PGM was found to be a valid model in detecting segmental length discrepancy when based on the location of the joint centers compared to X-ray. A variance was noted in the femur and tibial segmental length. The impact of this inconsistency in segmental length on kinematics and kinetics should be further evaluated.

Keywords: gait model; Plug-in-Gait; joint center; segmental length

1. Introduction

Leg length discrepancy (LLD) is a significant factor influencing several pathological and physiological conditions such as foot pathologies [1,2], low back pain [3,4], functional scoliosis in children [5], osteoarthritis of the hip and knee [6], impaired functional outcomes and patient satisfaction after total hip replacement [7,8]. Anatomic LLD is defined as the structural difference between the lengths of the two limbs measured from the femoral head to the distal tibia [9–11].

Various imaging techniques have been used to measure anatomic leg length [6,12]. Radiography is considered the gold standard for measurement, with accepted methods such as full limb radiographs, scanograms, computerized tomography and computerized digital radiographs. These methods are highly reliable and valid but are also expensive, not feasible for everyone and expose the subject to radiation, which limits their use in routine clinical settings.

Three-dimensional motion analysis is extensively used today thus, improving a comprehensive understanding of gait in musculoskeletal disorders. It also assists in detecting gait deviations and impairments underlying reduced function, clinical decision making, quantifying rehabilitation

effectiveness and treatment intervention [13,14]. Gait analysis is based on biomechanical gait models calculating joint kinematics [15,16]. No previous study has validated the ability of a gait model to detect anatomical LLD. If a LLD measurement is found valid, three-dimensional motion analysis can assist in detecting anatomic LLD.

The Plug-in-Gait model (PGM) (Vicon®, Oxford, UK) is one of the widely used biomechanical gait models, implementing a well-established predictive model [15,17]. The lower-body PGM divides the body into seven segments linked by joints with three degrees of freedom. The position of each joint is defined within its proximal segment and used to define its distal segment. The PGM extracts the experimental marker trajectories and generates virtual marker trajectories including joint centers. Assumed rigid body segments include the pelvis, femurs, tibias and feet. Femur and tibia segment length are calculated from joint center to joint center; the femur segment length is measured from the hip joint center (HJC) to the knee joint center (KJC); the tibia segment length is measured from the knee joint center (KJC) to the ankle joint center (AJC) [18].

The main aim of the present study was to evaluate the capability of the PGM in detecting anatomical LLD. Specifically, to test the correlation between the femur and tibia segmental length discrepancy as measured by the PGM comparing to gold standard imaging such as standing anteroposterior (AP) radiography and computed tomography (CT) supine scanogram, as well as the correlation between segmental lengths measured by both methods.

2. Methods

2.1. Participants

The study design was cross-sectional and comprised a group of patients who were referred for a gait analysis evaluation due to a suspected LLD affecting their gait, over a period of 6 months. After receiving approval from the Hospital Ethics Committee, 15 participants, 10 children—mean age 14 years (10–16), BMI (body mass index) 20.38 and 5 adults—mean age 44 years (42–50), BMI 25.64, who had undergone gait analysis and a full lower limb X-ray, were enrolled to the study.

2.2. Motion Capture

Anthropometrical measurements performed included—inter anterior superior iliac spine (ASIS) distance, distance of the right and left ASIS to the respective medial malleolus (MM) (clinical leg length), right and left knee, ankle width and tibial torsion measured by an intermalleolar angle in prone position. Subsequently, 13 reflective passive skin markers were placed on the pelvis and lower limbs, adhering to the PGM protocol [15]. Thigh and shank wand markers were aligned using the mirror method [19]. The thigh wand was aligned co-linearly with the HJC (greater trochanter) and the knee and shank marker were attached co-linearly with the knee and ankle markers [19].

Three-dimensional motion analysis was obtained by 8 MX3 cameras (Vicon Motion Systems®, Oxford, UK) and the Nexus® software (Version 1.8, Vicon Motion Systems®, UK, 2013). Following a standard protocol, a static calibration trial was performed for each subject while standing. All subjects' measurements, marker placement and alignment were performed by the primary experienced investigator in gait analysis. Calculated subject measurements were extracted from the static measurements file.

2.3. Imaging

All subjects' anatomic leg length was measured by a standing X-ray calibrated by a 54.2 cm metal ball for the children's group or a supine CT scanogram for the adult group, due to the height limitation in standing X-ray imaging. CT scanogram measurements, including left and right femur, tibia and total leg length were extracted from the imaging report. As for the standing X-ray, TraumaCad® software (Version 2.5, Brainlab®, Petach-Tikva, Israel, 2017) provided the investigator with a full set of wizards and digital measurement tools, using digital on-screen images [20]. The femur length was

measured from the proximal edge of the head of the femur to the distal end of the femoral condyle; the tibia length was measured from the tibia plateau to the tibia plafond. All X-ray measurements were performed by one of the investigators (B.D.), an experienced clinician in radiographic measurements, using TraumaCad® software which has been previously validated [20].

2.4. Data Analysis

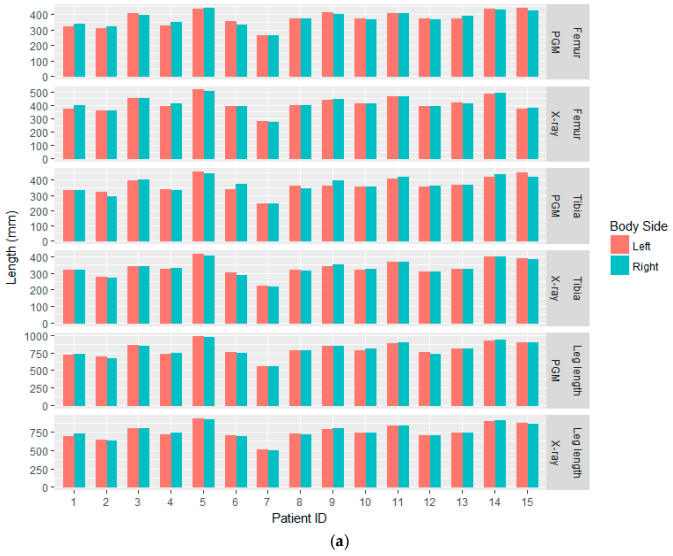
The femur and tibia segmental length, total X-ray length and clinical leg length (ASIS to MM) were checked for symmetry. The paired-t test assessed the difference between both methods when measuring the femur and tibia segmental length discrepancy, and the leg length discrepancy as measured by X-ray and clinically. Pearson's correlation assessed the association between methods when measuring segmental length, irrespective of the magnitude differences.

3. Results

Symmetricity is presented in Figure 1a. Lower limb measurements in all subjects were found symmetrical for both methods, including femur and tibia segmental length, X-ray total leg length and clinical leg length. Similar distributions were found between sides (Figure 1b). No differences were found for the femur t(14) = 1.06, $p = 0.3$ and tibia t(14) = −0.76, $p = 0.45$ segmental length for both methods when measuring discrepancies between sides (Table 1). In addition, no difference was found when comparing total X-ray leg length discrepancy to clinical leg length discrepancy t(14) = 1.33, $p = 0.2$ (Table 1).

Table 1. Plug-in-Gait-model (PGM) versus X-ray segmental length, total X-ray length, clinical leg length and discrepancies (mm). Significance represent comparison of mean discrepancies. Level of significance—$p < 0.01$.

Segment	Left (Mean)	Right (Mean)	Mean Discrepancy (SD)	Significance
PGM Femur length	372	371	0.66 (13.17)	$p = 0.30$
X-ray Femur length	410	413	−2.93 (9.63)	
PGM Tibia length	367	368	−1.60 (19.42)	$p = 0.45$
X-ray Tibia length	331	329	2.06 (7.01)	
X-ray total leg length	753	754	−1.0 (14.71)	$p = 0.2$
Clinical leg length	802	799	2.33 (14.12)	



(a)

Figure 1. *Cont.*

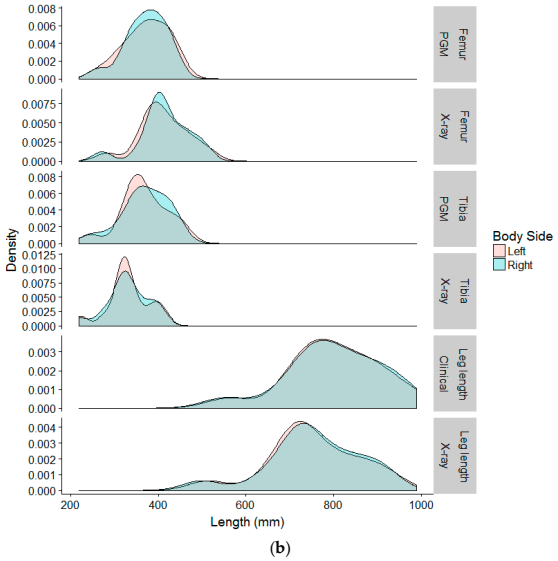


Figure 1. (**a**) Symmetricity of 15 participants for all lower limb measurements in both methods. Patient ID 1–10 children, 11–15 adults; (**b**) Density plot comparing distribution between sides for each measurement. PGM: Plug-in-Gait-model.

High correlations were found between methods when measuring segmental length (Figure 2); left femur length, r = 0.808, $p \leq 0.001$, left tibia length, r = 0.963, $p \leq 0.001$, right femur length, r = 0.868, $p \leq 0.001$, right tibia length, r = 0.933, $p \leq 0.001$. A significant difference was found in both methods when measuring the femur and tibia segmental length ($p < 0.001$) (Figure 3). The femur X-ray length was found to be significantly longer than the femur PGM length measurement; conversely, the tibia X-ray length was found to be significantly shorter than the tibia PGM length.

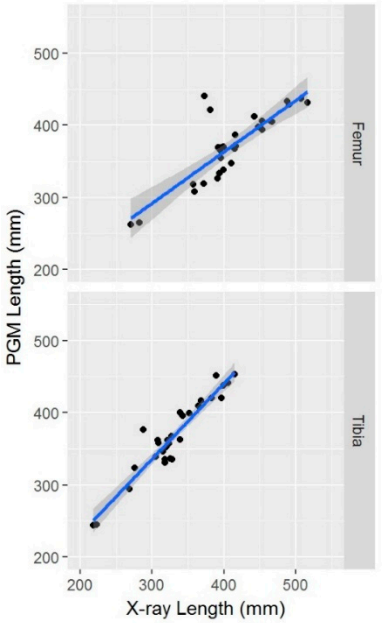


Figure 2. Correlations between femur and tibia PGM and X-ray segmental length.

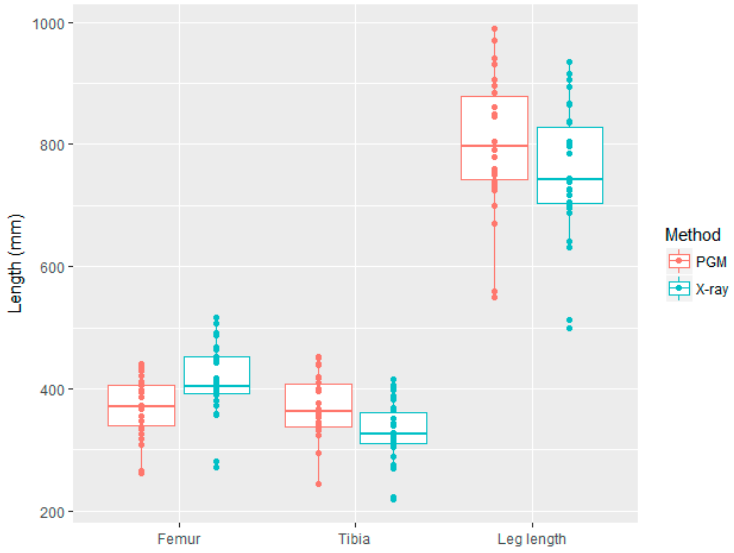


Figure 3. Differences in the median, quartiles, extreme values and outlier subjects for segmental and leg length measured by PGM and X-ray.

4. Discussion

Herein, we compared femur and tibia segmental length measurements using the PGM to detect anatomical discrepancy compared to X-ray measurements. Our results revealed that the PGM is highly valid and reliable in detecting anatomical difference in segmental length. Minimal differences in segmental discrepancy between sides were found when comparing both methods, with a mean difference of 3.6 mm in the femur and the tibia segmental length. Participants' measurements were found symmetrical with no significant difference in all lower limb measurements. A high correlation was found between methods, however, a significant difference in absolute values of the two measurements was found. Femoral length as calculated by the PGM was shorter by 18–21 mm; the tibial segmental length was shorter by 52–53 mm when X-rayed. The difference in segmental length of the femur was attributed to the measuring method. Femur segmental length as measured by the PGM was based on the joint center location as opposed to the X-ray where measurement started from the proximal edge of the femur head to the distal end of the femoral condyle. However, the tibias segments were relatively similarly measured in both methods, and despite difference that might be attributed to measuring methods, it cannot explain the large discrepancy found, and thus should be further investigated.

Radiographic evaluations either by standing X-ray or CT scanogram are considered the gold standard for measuring images. Computed radiography used for measuring segmental length has been found to be valid and reliable [20]. Radiographs calibrated using a 1-inch reference metal ball supported by a designated software program (TraumaCad®) have been found to have high intra and inter-observer reliability (Intraclass correlation coefficient (ICC) 0.91–0.95, respectively) and a standard deviation of 3.61 to 4.65 mm when measuring femoral and tibial length, respectively [20]. Sabharwal et al. reported a high inter and intra-observer reliability for scanogram (ICC 0.975–0.995, respectively) as well as standing teleroentgenogram (ICC 0.939–0.996) [21]. The mean absolute difference for intra-observer and inter-observer reliability was 1.5 to 2.6 mm and 2.6 mm, respectively for scanograms and 1.5 to 4.6 mm and 3 mm, respectively for standing radiographs. In summary, imaging is a highly reliable measurement tool, with a minimum estimated margin of error.

The PGM divides the body into seven segments (pelvis, two femurs, tibias and feet) [15]. The segments are defined from the measured positions of the markers, subjects' measurements and model calculation. Its accuracy is limited, relying on the examiner's ability to formulate an accurate anthropometric measurement such as the distance from the ASIS to MM, the distance between the right and left ASIS, knee and ankle width and tibial torsion, as well as accurate marker placement. In this study,

all measurements and marker placements were performed by the same examiner experienced in gait analysis which has been shown to improve reliability [22,23]. Moreover, anthropometric measurements assessed by experienced examiners have found no considerable effect on joint kinematics [24], thus, the likelihood that most differences found in the tibia segmental length were due to model calculation.

In the PGM, body segment parameters are based on a simple relationship described by Dempster et al. [25]. The location of the hip, knee, and ankle joint centers are calculated relative to the associated embedded coordinate system origin of the segments. Hip joint centering algorithm is based on a model developed at Newington Children's Hospital in 1981 analyzing radiographic studies of 25 hip studies [15]. The HJC was defined in the pelvis segment, using the pelvis width (right ASIS to left ASIS) and leg length (ASIS to MM) as scaling factors [15]. The ASIS trochanteric distance, mean leg length, pelvis width, marker radius and fixed radians calculated the offset vectors of the two HJCs. However, using a more accurate method to define the hip joint center could lead to a more accurate estimation of the femoral length [26]. The KJC and AJC's location were also determined by the knee and ankle width measurements [18].

HJC localization based on a regression equation has been found to be inaccurate resulting in a 30 $\pm$ 6 mm margin of error compared to a three-dimensional ultrasound, based on a population of healthy adults [17]. Leardini reported similar results found in a sample of 11 male adult able-bodied volunteers, where the HJC estimation was at a distance of 29 $\pm$ 8 mm of a measurement obtained by a roentgen stereophotogrammetric analysis [27]. Assi et al. found, a 25 mm $\pm$ 10 between HJC calculated by a PGM and a reference calculation by EOS imaging in 11 typically developed children [28]. In a CP group, the difference was 21 $\pm$ 10 mm. These findings can contribute to the differences in femoral length found in our study. The propagation of the errors in the localization of the hip joint center on kinematics and kinetics has been previously evaluated in the literature [29–31] and demonstrated that HJC misplacement could result in significant errors on both hip and knee kinematics and kinetics.

Our results imply significant variance when calculating the KJC and AJC's location as determined by the PGM calculation. As for the KJC, the importance of an accurate definition of the location of anatomical landmarks has been shown to have a significant effect on sagittal and knee joint moments, with a 25% disparity [32]. Sinclair el al found KJC localization to significantly affect coronal and transverse plane angulation using different KJC estimation techniques during walking among 12 male participants and weaker test retest reliability for the PGM [33]. As for the AJC, the PGM identifies the AJC based on the location of the knee and hip joint centers [18] and has previously produced errors when identifying the AJC. An AJC calculated by the PGM was found to significantly differ from the AJC calculated by a medial and lateral malleoli model [34]. The distances between two AJCs in the posterior-anterior, medial-lateral and inferior-superior directions were found to be approximately 6.3, 7.7 and 8.2 (mm). These results also concur with our findings, taking into consideration that the tibia segment is affected by the KJCs and AJCs location. However, the effect of our findings as to the tibia length and the byproduct of the KJC and AJC's location on the angulation calculations of the model are unknown. The impact of this variance in the localization of the KJCs and AJCs on kinematics and kinetics should be further assessed.

In conclusion, PGM was found to be a valid model in detecting segmental length discrepancy based on the joint centers' location compared to X-ray measurement. A variance is present in the femoral and tibial segmental length as measured by the PGM compared to the X-ray. Impact of this inconsistency in segmental length on kinematics and kinetics should be further evaluated.

Author Contributions: Sam Khamis is responsible for the design of the study, acquisition, analysis, and interpretation of data for the work, and writing the manuscript. Barry Danino, is responsible for critically revising the manuscript. Shmuel Springer, is responsible for study interpretation and final approval of submitted version. Dror Ovadia, is responsible for critically revising the manuscript. Eli Carmeli, is responsible for final approval of submitted version.

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References

1. Sanhudo, J.A.; Gomes, J.L. Association between leg length discrepancy and posterior tibial tendon dysfunction. *Foot Ankle Spec.* **2014**, *7*, 119–126. [CrossRef] [PubMed]
2. Mahmood, S.; Huffman, L.K.; Harris, J.G. Limb-length discrepancy as a cause of plantar fasciitis. *J. Am. Podiatr. Med. Assoc.* **2010**, *100*, 452–455. [CrossRef] [PubMed]
3. Vink, P.; Huson, A. Lumbar back muscle activity during walking with a leg inequality. *Acta Morphol. Neerlando Scand.* **1987**, *25*, 261–271.
4. Defrin, R.; Ben Benyamin, S.; Aldubi, R.D.; Pick, C.G. Conservative correction of leg-length discrepancies of 10 mm or less for the relief of chronic low back pain. *Arch. Phys. Med. Rehabil.* **2005**, *86*, 2075–2080. [CrossRef] [PubMed]
5. Raczkowski, J.W.; Daniszewska, B.; Zolynski, K. Functional scoliosis caused by leg length discrepancy. *Arch. Med. Sci.* **2010**, *6*, 393–398. [CrossRef] [PubMed]
6. Harvey, W.F.; Yang, M.; Cooke, T.D.; Segal, N.A.; Lane, N.; Lewis, C.E.; Felson, D.T. Association of leg-length inequality with knee osteoarthritis: A cohort study. *Ann. Intern. Med.* **2010**, *152*, 287–295. [CrossRef] [PubMed]
7. Iversen, M.D.; Chudasama, N.; Losina, E.; Katz, J.N. Influence of self-reported limb length discrepancy on function and satisfaction 6 years after total hip replacement. *J. Geriatr. Phys. Ther.* **2011**, *34*, 148–152. [CrossRef] [PubMed]
8. Fujimaki, H.; Inaba, Y.; Kobayashi, N.; Tezuka, T.; Hirata, Y.; Saito, T. Leg length discrepancy and lower limb alignment after total hip arthroplasty in unilateral hip osteoarthritis patients. *J. Orthop. Sci.* **2013**, *18*, 969–976. [CrossRef] [PubMed]
9. Baylis, W.J.; Rzonca, E.C. Functional and structural limb length discrepancies: Evaluation and treatment. *Clin. Podiatr. Med. Surg.* **1988**, *5*, 509–520. [PubMed]
10. Danbert, R.J. Clinical assessment and treatment of leg length inequalities. *J. Manip. Physiol. Ther.* **1988**, *11*, 290–295.
11. Walsh, M.; Connolly, P.; Jenkinson, A.; O'Brien, T. Leg length discrepancy—An experimental study of compensatory changes in three dimensions using gait analysis. *Gait Posture* **2000**, *12*, 156–161. [CrossRef]
12. Sabharwal, S.; Kumar, A. Methods for assessing leg length discrepancy. *Clin. Orthop. Relat. Res.* **2008**, *466*, 2910–2922. [CrossRef] [PubMed]
13. Baker, R. Gait analysis methods in rehabilitation. *J. Neuroeng. Rehabil.* **2006**, *3*, 4. [CrossRef] [PubMed]
14. Tugui, R.D.; Antonescu, D. Cerebral palsy gait, clinical importance. *Maedica* **2013**, *8*, 388–393. [PubMed]
15. Davis, R.B.; Ounpuu, S.; Tyburski, D.; Gage, J.R. A gait analysis data collection and reduction technique. *Hum. Mov. Sci.* **1991**, *10*, 575–587. [CrossRef]
16. Kadaba, M.P.; Ramakrishnan, H.K.; Wootten, M.E. Measurement of lower extremity kinematics during level walking. *J. Orthop. Res.* **1990**, *8*, 383–392. [CrossRef] [PubMed]
17. Sangeux, M.; Peters, A.; Baker, R. Hip joint centre localization: Evaluation on normal subjects in the context of gait analysis. *Gait Posture* **2011**, *34*, 324–328. [CrossRef] [PubMed]
18. Vicon®. *Plug-in-Gait Modelling Instructions*; Oxford Metrics Ltd.: Oxford, UK, 2015.
19. Kirtley, C. Sensitivity of the modified Helen Hayes model to marker placement errors. In Proceedings of the Seventh International Symposium on the 3-D Analysis of Human Movement, Newcastle, UK, 10–12 July 2002.
20. Segev, E.; Hemo, Y.; Wientroub, S.; Ovadia, D.; Fishkin, M.; Steinberg, D.M.; Hayek, S. Intra- and interobserver reliability analysis of digital radiographic measurements for pediatric orthopedic parameters using a novel PACS integrated computer software program. *J. Child. Orthop.* **2010**, *4*, 331–341. [CrossRef] [PubMed]
21. Sabharwal, S.; Zhao, C.; McKeon, J.; Melaghari, T.; Blacksin, M.; Wenekor, C. Reliability analysis for radiographic measurement of limb length discrepancy: Full-length standing anteroposterior radiograph versus scanogram. *J. Pediatr. Orthop.* **2007**, *27*, 46–50. [CrossRef] [PubMed]
22. Leigh, R.J.; Pohl, M.B.; Ferber, R. Does tester experience influence the reliability with which 3D gait kinematics are collected in healthy adults? *Phys. Ther. Sport* **2014**, *15*, 112–116. [CrossRef] [PubMed]
23. Sinclair, J.; Hebron, J.; Taylor, P.J. The influence of tester experience on the reliability of 3D kinematic information during running. *Gait Posture* **2014**, *40*, 707–711. [CrossRef] [PubMed]

24. Krumm, D.; Cockcroft, J.; Zaumseil, F.; Odenwald, S.; Milani, T.L.; Louw, Q. Analytical evaluation of the effects of inconsistent anthropometric measurements on joint kinematics in motion capturing. *Gait Posture* **2016**, *46*, 1–4. [CrossRef] [PubMed]
25. Dempster, W.T.; Gabel, W.C.; Felts, W.J. The anthropometry of the manual work space for the seated subject. *Am. J. Phys. Anthropol.* **1959**, *17*, 289–317. [CrossRef] [PubMed]
26. Kainz, H.; Carty, C.P.; Modenese, L.; Boyd, R.N.; Lloyd, D.G. Estimation of the hip joint centre in human motion analysis: A systematic review. *Clin. Biomech.* **2015**, *30*, 319–329. [CrossRef] [PubMed]
27. Leardini, A.; Cappozzo, A.; Catani, F.; Toksvig-Larsen, S.; Petitto, A.; Sforza, V.; Cassanelli, G.; Giannini, S. Validation of a functional method for the estimation of hip joint centre location. *J. Biomech.* **1999**, *32*, 99–103. [CrossRef]
28. Assi, A.; Sauret, C.; Massaad, A.; Bakouny, Z.; Pillet, H.; Skalli, W.; Ghanem, I. Validation of hip joint center localization methods during gait analysis using 3D EOS imaging in typically developing and cerebral palsy children. *Gait Posture* **2016**, *48*, 30–35. [CrossRef] [PubMed]
29. Stagni, R.; Leardini, A.; Cappozzo, A.; Grazia Benedetti, M.; Cappello, A. Effects of hip joint centre mislocation on gait analysis results. *J. Biomech.* **2000**, *33*, 1479–1487. [CrossRef]
30. Kiernan, D.; Malone, A.; O'Brien, T.; Simms, C.K. The clinical impact of hip joint centre regression equation error on kinematics and kinetics during paediatric gait. *Gait Posture* **2015**, *41*, 175–179. [CrossRef] [PubMed]
31. Kainz, H.; Carty, C.P.; Maine, S.; Walsh, H.P.J.; Lloyd, D.G.; Modenese, L. Effects of hip joint centre mislocation on gait kinematics of children with cerebral palsy calculated using patient-specific direct and inverse kinematic models. *Gait Posture* **2017**, *57*, 154–160. [CrossRef] [PubMed]
32. Thewlis, D.; Richards, J.; Bower, J. Discrepancies in knee joint moments using common anatomical frames defined by different palpable landmarks. *J. Appl. Biomech.* **2008**, *24*, 185–190. [CrossRef] [PubMed]
33. Sinclair, J.; Hebron, J.; Taylor, P.J. The test-retest reliability of knee joint center location techniques. *J. Appl. Biomech.* **2015**, *31*, 117–121. [CrossRef] [PubMed]
34. Nair, S.P.; Gibbs, S.; Arnold, G.; Abboud, R.; Wang, W. A method to calculate the centre of the ankle joint: A comparison with the Vicon Plug-in-Gait model. *Clin. Biomech.* **2010**, *25*, 582–587. [CrossRef] [PubMed]