Journal of Biomechanics 49 (2016) 1698–1704

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

A principal component analysis approach to correcting the knee flexion axis during gait

Elisabeth Jensen [a,b], Vipul Lugade [a,c], Jeremy Crenshaw [d], Emily Miller [b], Kenton Kaufman [b,*]

[a] Mayo Graduate School, Biomedical Engineering and Physiology Track, Mayo Clinic, Rochester, MN 55905, USA
[b] Motion Analysis Laboratory, Division of Orthopedic Research, Mayo Clinic, Charlton North L-110L, Rochester, MN 55905, USA
[c] Whitaker International Program, Chiang Mai University, Department of Physical Therapy, Chiang Mai 50200, Thailand
[d] Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE 19713, USA

ARTICLE INFO

Article history:
Accepted 28 March 2016

Keywords:
Gait analysis
Kinematics
Axis of rotation
Marker placement
Correction algorithm

ABSTRACT

Accurate and precise knee flexion axis identification is critical for prescribing and assessing tibial and femoral derotation osteotomies, but is highly prone to marker misplacement-induced error. The purpose of this study was to develop an efficient algorithm for post-hoc correction of the knee flexion axis and test its efficacy relative to other established algorithms. Gait data were collected on twelve healthy subjects using standard marker placement as well as intentionally misplaced lateral knee markers. The efficacy of the algorithm was assessed by quantifying the reduction in knee angle errors. Crosstalk error was quantified from the coefficient of determination (r^2) between knee flexion and adduction angles. Mean rotation offset error (α_o) was quantified from the knee and hip rotation kinematics across the gait cycle. The principal component analysis (PCA)-based algorithm significantly reduced r^2 ($p < 0.001$) and caused $\alpha_{o,knee}$ to converge toward $11.9 \pm 8.0°$ of external rotation, demonstrating improved certainty of the knee kinematics. The within-subject standard deviation of $\alpha_{o,hip}$ between marker placements was reduced from $13.5 \pm 1.5°$ to $0.7 \pm 0.2°$ ($p < 0.001$), demonstrating improved precision of the knee kinematics. The PCA-based algorithm performed at levels comparable to a knee abduction–adduction minimization algorithm (Baker et al., 1999) and better than a null space algorithm (Schwartz and Rozumalski, 2005) for this healthy subject population.

1. Introduction

Gait analysis provides critical data on patient dynamic functionality upon which orthopedic surgeons rely for pre- and post-intervention assessments (Filho et al., 2008; Lofterod and Terjesen, 2008; Saraph et al., 2002; Wren et al., 2011). Alternative forms of assessment, such as static magnetic resonance imaging (MRI), physical examination, or visual analysis, do not provide accurate and precise quantification of a patient's capabilities during dynamic activities. Among patients with suspected tibial or femoral torsion, knee and hip kinematics are a critical component of de-rotation osteotomy decisions (Aminian et al., 2003; DeLuca et al., 1997; Ounpuu et al., 2002). Gait analysis is consulted to identify whether surgery is required to create neutral alignment of the lower extremity segments during stance phase and reduce off-axis loading of the knee (Bennett et al., 1985; Stefko et al., 1998). These surgeries are invasive, expensive, and require lengthy recovery periods (Krengel and Staheli, 1992; Staheli et al., 1985), placing significant weight on the validity and reliability of the measured gait kinematics.

Motion-capture marker misplacement has previously been identified as the largest source of between-laboratory kinematic variability – accounting for up to 75% of the overall variance (Gorton et al., 2009) – as well as within-laboratory variability (Kadaba et al., 1989). Therefore, improving the validity and reliability of gait kinematics by addressing human marker placement error is critical to improving the internal validity of gait analyses. Derotation osteotomy decisions depend specifically on the placement of the anatomical markers that define the knee rotation axis. Misplacement of these markers can lead to mean rotation offset error of the hip and knee as well as crosstalk between knee flexion and adduction angles (Baker et al., 1999; Kadaba et al., 1990; Piazza and Cavanagh, 2000), and, ultimately, ineffective or harmful surgical interventions. A method is needed to consistently and reliably ensure correct identification of the knee flexion axis.

Other knee flexion axis correction techniques have been explored in the literature, including iterative, statistical, and hardware-based approaches (Baker et al., 1999; Charlton et al.,

* Corresponding author. Tel.: +507 284 2262; fax: +507 266 2227.
E-mail address: kaufman.kenton@mayo.edu (K. Kaufman).

http://dx.doi.org/10.1016/j.jbiomech.2016.03.046
0021-9290/

marker placement on young (less than 34) and healthy (BMI less than 26) subjects. In a previous study, an r^2 of 0.36 ± 0.60 was found for standard marker placement on young (mean of 22), healthy (mean BMI of 22.2) subjects (Schache et al., 2006). These results reinforce the importance of using a reliable correction algorithm.

A limitation of the current study is that although the KJC location was substantially affected by the marker misplacement (as evidenced by the shifted mean flexion–extension offset), two of the three tested algorithms were not designed to correct the KJC. In a normal clinical setting, this degree of marker misplacement is not anticipated; nor is marker misplacement expected to be isolated to the lateral knee marker. However, the unreliability of the mean flexion extension offset should be considered when applying these algorithms and care should be taken in interpreting knee hyperextension or flexion contracture. Further improvements would include better identification of the anterior-posterior position of the KJC.

Subsequent work is needed to compare the effectiveness of the current algorithms under various challenging conditions of pathologic knees. We expect to find greater algorithm differentiation under pathologic conditions than was observed in the healthy population, particularly when comparing the PCA and KAAM algorithms. One example is patients with frontal plane knee laxity, which may be due to conditions such as collagen disorders (e.g. Ehlers–Danlos syndrome) or impact-induced ligament injury. Frontal plane knee laxity is a self-reported weak area of the KAAM method (Baker et al., 1999), but we hypothesize that the proposed PCA algorithm will be robust in these patients as long as an adequate ratio of flexion–extension to abduction–adduction excursion is retained. A similarly challenging application is patients with restricted flexion–extension excursion, such as individuals with arthritis (Brinkmann and Perry, 1985) or toe-walkers (Davids et al., 1999). The algorithms should also be tested in overweight patients with redundant tissue, where marker placement over bony landmarks is more challenging (Besier et al., 2003) and increased skin motion artifact is expected (Shultz et al., 2009). Comparing the correction algorithms in these kinds of challenging patient populations will provide greater insight into the strengths and weaknesses of each algorithm.

Another PCA-based flexion axis correction method has demonstrated a significant crosstalk reduction in a population of older adults (Baudet et al., 2014). The Baudet algorithm is distinctive from the current PCA algorithm as the input is the three Euler angles as opposed to transformed data projected into a 2D plane. Statistically significant crosstalk reduction was demonstrated, but it is difficult to ascertain the magnitude of the change given that the final values were rounded. Furthermore, no direct comparison was made to other algorithms in the literature. Further analysis of this method is required to determine its effectiveness relative to the currently proposed PCA algorithm.

We have provided evidence for increased certainty and precision of the knee kinematics with the PCA correction algorithm over uncorrected kinematics, which indicates improvement in validity and reliability of the data. By demonstrating a statistically significant and meaningful reduction in downstream kinematic errors, we have shown improvement in the *certainty* of the knee flexion axis. Further study is needed to quantify the true accuracy of the algorithm by comparing the corrected gait analysis-based kinematics with a gold standard of fluoroscopy-based kinematics (Li et al., 2008). We have also demonstrated that the *precision* of the flexion axis is likely improved by the algorithm, as the within-limb variability of the knee rotation angle was decreased. This decrease in the observed variance between tests also demonstrates increased test-retest *reliability* (Streiner and Norman, 2006). All of these improvements combined provide evidence for the *validity* of the PCA algorithm measurements for surgical assessments such as de-rotational osteotomy. With this correction, much greater weight can be placed on the measurements for surgical interventions and outcome evaluations in the future.

Conflict of interest statement

The authors have no conflict of interest to report.

Acknowledgments

Funding for this study was provided by NIH T32 HD07447, NIH T32 AR56950, and by the Mayo Graduate School. The authors would like to thank Kathie Bernhardt, Meegan van Straaten, and Lindsey Back for their help with data collection and analysis. The authors are grateful to Scott Selbie for providing software support and valuable feedback.

References

Aminian, A., Vankoski, S.J., Dias, L., Novak, R.A., 2003. Spastic hemiplegic cerebral palsy and the femoral derotation osteotomy: effect at the pelvis and hip in the transverse plane during gait. J. Pediatr. Orthop. 23, 314–320.
Baker, R., Finney, L., Orr, J., 1999. A new approach to determine the hip rotation profile from clinical gait analysis data. Hum. Mov. Sci. 18, 655–667.
Baudet, A., Morisset, C., d'Athis, P., Maillefert, J.F., Casillas, J.M., Ornetti, P., Laroche, D., 2014. Cross-talk correction method for knee kinematics in gait analysis using principal component analysis (PCA): a new proposal. PLoS One 9, e102098.
Bell, K.J., Ounpuu, S., DeLuca, P.A., Romness, M.J., 2002. Natural progression of gait in children with cerebral palsy. J. Pediatr. Orthop. 22, 677–682.
Bennett, J.T., Bunnell, W.P., MacEwen, G.D., 1985. Rotational osteotomy of the distal tibia and fibula. J. Pediatr. Orthop. 5, 294–298.
Besier, T.F., Sturnieks, D.L., Alderson, J.A., Lloyd, D.G., 2003. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. J. Biomech. 36, 1159–1168.
Brinkmann, J.R., Perry, J., 1985. Rate and range of knee motion during ambulation in healthy and arthritic subjects. Phys. Ther. 65, 1055–1060.
Charlton, I.W., Tate, P., Smyth, P., Roren, L., 2004. Repeatability of an optimised lower body model. Gait Posture 20, 213–221.
Davids, J.R., Foti, T., Dabelstein, J., Bagley, A., 1999. Voluntary (normal) versus obligatory (cerebral palsy) toe-walking in children: a kinematic, kinetic, and electromyographic analysis. J. Pediatr. Orthop. 19, 461–469.
Davis, R., Ounpuu, S., Tyburski, D., Gage, J.R., 1991. A gait analysis data collection and reduction technique. Hum. Mov. Sci. 10, 575–587.
DeLuca, P.A., Davis, R.B., Ounpuu, S., Rose, S., Sirkin, R., 1997. Alterations in surgical decision making in patients with cerebral palsy based on three-dimensional gait analysis. J. Pediatr. Orthop. 17, 608–614.
Ehrig, R.M., Taylor, W.R., Duda, G.N., Heller, M.O., 2007. A survey of formal methods for determining functional joint axes. J. Biomech. 40, 2150–2157.
Filho, M.Cd.M., Yoshida, R., Carvalho, Wd.S., Stein, H.E., Novo, N.F., 2008. Are the recommendations from three-dimensional gait analysis associated with better postoperative outcomes in patients with cerebral palsy? Gait Posture 28, 316–322.
Fullenkamp, A.M., 2005. Clinical usefulness of four functional knee axis alignment, In: Proceedings of the ASB 29th Annual Meeting. ISB XXth Congress, Cleveland, OH.
Gorton 3rd, G.E., Hebert, D.A., Gannotti, M.E., 2009. Assessment of the kinematic variability among 12 motion analysis laboratories. Gait Posture 29, 398–402.
Groen, B.E., Geurts, M., Nienhuis, B., Duysens, J., 2012. Sensitivity of the OLGA and VCM models to erroneous marker placement: effects on 3D-gait kinematics. Gait Posture 35, 517–521.
Halvorsen, K., Lesser, M., Lundberg, A., 1999. A new method for estimating the axis of rotation and the center of rotation. J. Biomech. 32, 1221–1227.
Harrington, M.E., Zavatsky, A.B., Lawson, S.E., Yuan, Z., Theologis, T.N., 2007. Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. J. Biomech. 40 (3), 595–602.
Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., 1990. Measurement of lower extremity kinematics during level walking. J. Orthop. Res. 8, 383–392.
Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., Gainey, J., Gorton, G., Cochran, G. V.B., 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J. Orthop. Res. 7, 849–860.
Krengel, W.F., Staheli, L.T., 1992. Tibial totational osteotomy for idiopathic torsion – a comparison of the proximal and distal osteotomy levels. Clin. Orthop. Relat. Res., 285–289.

Lafortune, M.A., Cavanagh, P.R., Sommer 3rd, H.J., Kalenak, A., 1992. Three-dimensional kinematics of the human knee during walking. J. Biomech. 25, 347–357.
Li, G., Van de Velde, S.K., Bingham, J.T., 2008. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. J. Biomech. 41, 1616–1622.
Lin, C.J., Guo, L.Y., Su, F.C., Chou, Y.L., Cherng, R.J., 2000. Common abnormal kinetic patterns of the knee in gait in spastic diplegia of cerebral palsy. Gait Posture 11, 224–232.
Lofterod, B., Terjesen, T., 2008. Results of treatment when orthopaedic surgeons follow gait-analysis recommendations in children with CP. Dev. Med. Child Neurol. 50, 503–509.
Ounpuu, S., DeLuca, P., Davis, R., Romness, M., 2002. Long-term effects of femoral derotation osteotomies: an evaluation using three-dimensional gait analysis. J. Pediatr. Orthop. 22, 139–145.
Pearson, K., 1901. On lines and planes of closest fit to systems of points in space. Philos. Mag. 2, 559–572.
Piazza, S.J., Cavanagh, P.R., 2000. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. J. Biomech. 33, 1029–1034.
Saraph, V., Zwick, E.B., Zwick, G., Steinwender, C., Steinwender, G., Linhart, W., 2002. Multilevel surgery in spastic diplegia: evaluation by physical examination and gait analysis in 25 children. J. Pediatr. Orthop. 22, 150–157.
Schache, A.G., Baker, R., Lamoreux, L.W., 2006. Defining the knee joint flexion–extension axis for purposes of quantitative gait analysis: an evaluation of methods. Gait Posture 24, 100–109.
Shultz, S.P., Sitler, M.R., Tierney, R.T., Hillstrom, H.J., Song, J., 2009. Effects of pediatric obesity on joint kinematics and kinetics during 2 walking cadences. Arch. Phys. Med. Rehabil. 90, 2146–2154.
Schwartz, M.H., Rozumalski, A., 2005. A new method for estimating joint parameters from motion data. J. Biomech. 38, 107–116.
Sestan, B., Kozic, S., Djapic, T., Ekl, D., 2008. Evaluation of a tibial torsiometer applicable to clinical practice. Orthopedics 31, 70.
Staheli, L.T., Corbett, M., Wyss, C., King, H., 1985. Lower-extremity rotational problems in children – normal values to guide management. J. Bone Jt. Surg. Am. 67A, 39–47.
Stefko, R.M., de Swart, R.J., Dodgin, D.A., Wyatt, M.P., Kaufman, K.R., Sutherland, D. H., Chambers, H.G., 1998. Kinematic and kinetic analysis of distal derotational osteotomy of the leg in children with cerebral palsy. J. Pediatr. Orthop. 18, 81–87.
Streiner, D.L., Norman, G.R., 2006. "Precision" and "accuracy": two terms that are neither. J. Clin. Epidemiol. 59, 327–330.
Wren, T.A., Otsuka, N.Y., Bowen, R.E., Scaduto, A.A., Chan, L.S., Sheng, M., Hara, R., Kay, R.M., 2011. Influence of gait analysis on decision-making for lower extremity orthopaedic surgery: baseline data from a randomized controlled trial. Gait Posture 34, 364–369.
Wren, T.A., Rethlefsen, S., Kay, R.M., 2005. Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. J. Pediatr. Orthop. 25, 79–83.