Available online at www.sciencedirect.com
SCIENCE DIRECT
Gait & Posture 23 (2006) 401–410
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Repeatability of a model for measuring multi-segment foot kinematics in children

J. Stebbins *, M. Harrington, N. Thompson, A. Zavatsky, T. Theologis

Oxford Gait Laboratory, Nuffield Orthopaedic Centre, Windmill Road, Headington, Oxford OX3 7LD, UK

Received 24 August 2004; received in revised form 19 January 2005; accepted 28 March 2005

Abstract

This study used a previously tested foot model and adapted it for use with children. A number of variations on this adapted model were implemented and tested for repeatability and accuracy on 15 healthy children on three occasions. These included redefinition of the long axes of the tibia and forefoot, assessment of the flexibility of the forefoot and evaluation of the variability of the wand marker on the heel for both static and dynamic trials. It was found that variations on the model produced only minimal changes in repeatability, the only significant change being elimination of the wand marker on the heel in the static trial, which reduced between-day variability of hindfoot motion in the transverse plane. However, some differences were evident in the mean values for all variations. Based on these results, the most accurate and appropriate version of the model is proposed, and average kinematic curves are presented based on the measurements from 14 healthy children.

Keywords: Foot; Kinematics; Children; Repeatability

1. Introduction

The measurement of three-dimensional lower body kinematics through the use of stereophotogrammetry has been well tested and validated over many years. Gait analysis now forms a major part of clinical decision making, particularly in the field of surgical treatment for children with cerebral palsy [1]. Conventional lower body models represent the pelvis, femur and lower leg as separate rigid bodies; however, the foot is routinely modelled only as a single vector, with no relative motion between or within its different segments. This provides inadequate information when determining treatment specific to the foot.

Measurement of foot kinematics is becoming increasingly common as motion analysis measuring systems become more accurate. Many research groups around the world are proposing multi-segment foot models, and it is important that the repeatability and clinical significance of these models be thoroughly investigated before they are routinely used to inform clinical decision-making. It is also necessary to standardise the analysis and reporting of results to allow comparisons between centres.

Most work to date has been carried out on healthy adult feet [2–11] and these studies are mainly limited to the stance phase of gait. A limited amount of work has also been conducted on pathological feet [7,12–14], again mainly in adults. No repeatability studies have been reported for measurements on children's feet. This population poses different challenges, the most significant being the small surface area of the foot and greater variability in gait [15]. There are many conditions that produce deformity in children's feet. For example, 90% of children with cerebral palsy develop some form of foot deformity resulting from abnormal forces being applied to the immature skeleton over periods of growth [16]. A valid and repeatable foot model for children is needed for understanding normal and pathological function, planning intervention and evaluating the outcome of treatment.

The purpose of the current study was to take our previously described multi-segment foot model validated for healthy adults [4] and adapt it for use in children over the entire gait cycle. Five variations of the adapted model were then tested to determine the most appropriate method for

* Corresponding author. Tel.: +44 1865 227609.
E-mail address: julie.stebbins@ndos.ox.ac.uk (J. Stebbins).

0966-6362/$ – see front matter
doi:10.1016/j.gaitpost.2005.03.002

overall relative motion between the tibia and hindfoot. However, the term ''inversion/eversion'' is meaningful to clinicians using this model, but it needs to be taken in the context of the definition described.

Taking into account repeatability and compatibility issues with the existing lower body model, it was decided to continue using the physical ''TOE'' marker to calculate the long axis of the forefoot, to eliminate use of the CPEG wand marker on the calcaneus, to use the conventional knee joint centre to calculate the long axis of the tibia, and to measure forefoot ''arch height'' relative to the plantar surface defined by lateral markers on the forefoot to allow estimation of error produced in forefoot supination as a result of rigid body assumptions. Mean angles from the 14 healthy children of this version of the model are shown in Fig. 5.

An awareness of the variability in measurement of inter-segment foot motion in children is vital for correct interpretation of results and should not be ignored when planning treatment and assessing outcomes. While a number of different variations of the model were assessed to achieve the optimal model for measuring foot motion, up to 78 variability was still apparent in the transverse plane. It was recognised that this may be in part due to inherent variability in children's gait. However, a significant factor is the consistency of marker placement between days on small feet. Therefore, clear protocols and practice in marker placement are crucial and improvements to fixation of the reflective markers should be considered.

This study provided a validated multi-segment foot model for use with children, which previously was unavailable. The model proposed here produced results consistent with previous studies of foot kinematics in adults [2,4–7] and expected foot motion during normal gait [22]. This validation allows clinical implementation of the model, with an understanding of its reliability. The results in kinematic patterns were found to be more consistent than the absolute values. Absolute measurements in the transverse plane were found to be the least consistent, but repeatability was improved when the wand marker was eliminated from use on the hindfoot. The difference between measuring angles in slightly different ways gave only negligible differences in results, allowing for some flexibility in implementation in the presence of severe deformity.

Acknowledgements

We acknowledge the generous support of Action Medical Research in funding this project. We would also like to thank Maria Seniorou and the rest of the team at the Oxford Gait Laboratory for their assistance, and the Centre for Statistics in Medicine, Oxford University for statistical support.

References

[1] Norlin R, Tkaczuk H. One-session surgery for correction of lower extremity deformities in children with cerebral palsy. J Pediatr Orthop 1985;5:208–11.
[2] MacWilliams BA, Cowley M, Nicholson DE. Foot kinematics and kinetics during adolescent gait. Gait Posture 2003;17:214–24.
[3] Woodburn J, Turner DE, Helliwell PS, Barker S. A preliminary study determining the feasibility of electromagnetic tracking for kinematics at the ankle joint complex. Rheumatology (Oxford) 1999;38:1260–8.
[4] Carson MC, Harrington ME, Thompson N, O'Connor JJ, Theologis TN. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. J Biomech 2001; 34:1299–307.
[5] Kidder SM, Abuzzahab Jr FS, Harris GF, Johnson JE. A system for the analysis of foot and ankle kinematics during gait. IEEE Trans Rehabil Eng 1996;4:25–32.
[6] Hunt AE, Smith RM, Torode M, Keenan AM. Inter-segment foot motion and ground reaction forces over the stance phase of walking. Clin Biomech 2001;16:592–600.
[7] Rattanaprasert U, Smith R, Sullivan M, Gilleard W. Three-dimensional kinematics of the forefoot, rearfoot, and leg without the function of tibialis posterior in comparison with normals during stance phase of walking. Clin Biomech 1999;14:14–23.
[8] Leardini A, Benedetti MG, Catani F, Simoncini L, Giannini S. An anatomically based protocol for the description of foot segment kinematics during gait. Clin Biomech 1999;14:528–36.
[9] Kepple TM, Stanhope SJ, Lohmann KN, Roman NL. A video-based technique for measuring ankle-subtalar motion during stance. J Biomed Eng 1990;12:273–80.
[10] Siegel KL, Kepple TM, O'Connell PG, Gerber LH, Stanhope SJ. A technique to evaluate foot function during the stance phase of gait. Foot Ankle Int 1995;16:764–70.
[11] Moseley L, Smith R, Hunt A, Gant R. Three-dimensional kinematics of the rearfoot during the stance phase of walking in normal young adult males. Clin Biomech 1996;11:39–45.
[12] Woodburn J, Helliwell PS, Barker S. Three-dimensional kinematics at the ankle joint complex in rheumatoid arthritis patients with painful valgus deformity of the rearfoot. Rheumatology 2002;41: 1406–1412.
[13] Wu WL, Su FC, Cheng YM, Huang PJ, Chou YL, Chou CK. Gait analysis after ankle arthrodesis. Gait Posture 2000;11:54–61.
[14] Theologis TN, Harrington ME, Thompson N, Benson MK. Dynamic foot movement in children treated for congenital talipes equinovarus. J Bone Joint Surg Br 2003;85:572–7.
[15] Stolze H, Kuhtz-Buschbeck JP, Mondwurf C, Johnk K, Friege L. Retest reliability of spatiotemporal gait parameters in children and adults. Gait Posture 1998;7:125–30.
[16] O'Connell PA, D'Souza L, Dudeney S, Stephens M. Foot deformities in children with cerebral palsy. J Pediatr Orthop 1998;18:743–7.
[17] Davis RB, Deluca PA. Clinical gait analysis. In: Harris GF., Smith P, editors. Human motion analysis. NJ, USA: IEEE Press; 1996. p. 17–42.
[18] Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 1983;105:136–44.
[19] Liu W, Siegler S, Hillstrom HJ, Whitney K. Three-dimensional, six-degrees-of-freedom kinematics of the human hindfoot during stance phase of level walking. Hum Move Sci 1997;16:283–98.
[20] Soutas-Little RW. The use of ''virtual markers'' in human movement analysis. Gait Posture 1996;4:176–7.
[21] Leardini A, Stagni R, O'Connor JJ. Mobility of the subtalar joint in the intact ankle complex. J Biomech 2001;34:805–9.
[22] Perry J. Gait analysis: normal and pathological function. NJ: Slack International, 1992.