Use of Quantitative Gait Analysis for the Evaluation of Prosthetic Walking Performance

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ABSTRACT

Prosthetists must be skilled in observational gait analysis to perform a rapid assessment of their client's gait in the clinic and make appropriate adjustments to the prosthesis to eliminate or reduce gait abnormalities. Quantitative gait evaluations are able to provide additional, objective information to supplement the clinical observation. Although quantitative gait analysis has become a clinically accepted means for evaluating and documenting certain pathologies that affect pediatric gait such as cerebral palsy and myelomeningocele, routine clinical quantitative gait analyses are not performed on lower-limb prosthesis users. Unfortunately, limitations in our understanding about the pathomechanics of amputee gait and the functions that need to be provided by prostheses inhibit our ability to effectively use quantitative gait data as a means to diagnose and treat observed gait deviations. Furthermore, data pertaining to amputee gait can be difficult to assess and interpret because the data can be highly influenced by the particular choice of prosthetic components, socket type, and suspension, as well as by the residual anatomy, abilities, and psychological well-being of the patient. Studies of prosthetic users reported in the literature tend to indicate a lack of consistency in quantitative gait measures, even in similar populations of amputee subjects who are walking with comparable prosthetic configurations. Therefore, the value of using these data individually for outcome measures is questionable. At present, quantitative gait analysis appears to be beneficial for documenting the rehabilitation progress of patients over time and may be useful for evaluating some prosthetic gaits, but the information may not necessarily enable the experienced clinician to make better decisions regarding prosthetic prescription or modifications. Nonetheless, it is important that we continue to strive to effectively integrate these quantitative measurements with the experience and skill of the prosthetist and the subjective feedback of the prosthetic user.

INTRODUCTION

A quantitative gait analysis is generally considered to be any objective means that can be used to measure walking performance. The procedure can be as simple as measuring step length with a ruler or determining cadence with a stopwatch, or it can be as sophisticated as full-body motion capture with state-of-the-art instrumentation. Regardless of the methods, the measurements that are collected are used to assess the quality of the gait and to characterize the motion. Observational gait analysis involves a subjective assessment of an individual's gait, but experienced individuals are often able to visually identify many of the same gait abnormalities that can be discerned with quantitative gait analysis. However, key advantages of quantitative gait analysis for persons with lower-limb pathologies are that the results allow for easy comparison of a patient's gait characteristics to an able-bodied pattern for a relatively quick determination of abnormal movements, and it documents a patient's gait at a particular point in time so rehabilitation progress can be tracked.

Using quantitative gait analyses to fully describe a person's gait generally entails the combination of a multitude of measurements, including temporal-spatial parameters, kinematics, kinetics, and energy expenditure. When presented with large quantities of descriptive measurements, wading through all of the data and picking out relevant information can take a tremendous amount of time and effort. However, the process can generally be facilitated by involving someone who is knowledgeable about the measures and skilled in analyzing and interpreting the data. Visual gait analysis, performed first-hand or by viewing a videotape recording of the subject's gait, can greatly aid with the interpretation of the quantitative gait data.

Once regarded as a research endeavor, quantitative gait analysis has now become a clinically accepted means for documenting and evaluating the characteristics of a person's gait, particularly in the presence of pathologies that affect walking. Presently, there are numerous clinical gait analysis laboratories dedicated to the evaluation of children with cerebral palsy, myelomeningocele, or other disabling conditions that affect walking. The results from these analyses are used by physicians and therapists to determine appropriate surgical interventions or courses of treatment for the child with the intent of improving walking efficiency and appearance. Gait analyses are typically performed before and after

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and utilizing gait measurement systems that enable different components to be compared in "real world" situations outside of the gait laboratory.

Many of the published quantitative gait studies seem to indicate that amputees are able to readily adapt to changes in their prostheses. Most prosthetists have probably noticed this effect in the clinic—they fit their client with a new prosthetic component, and visual gait analysis indicates no discernible difference from a previous prosthetic configuration. Experienced prosthetic users are able to readily adapt to minor, and major, prosthetic modifications. In those cases, their gait does not usually improve and they will often display the same gait pattern as before. Therefore, greater attention must be paid to gait training for new amputees, and retraining for more experienced users to break their bad habits and to instill proper form. For prosthetic users to achieve maximum benefit from new technology, they must be taught how to walk with their prostheses in such a manner that they take full advantage of the design features. Good gait requires that the user develop trust, security and confidence in his or her prosthesis, learning one's capabilities and identifying limitations, all of which take time and experience.

Even though statistically significant differences among components are usually not detected using quantitative gait measures, subjects often express clear preference for one component over another, suggesting that very subtle changes in gait may be detected by the user and be perceived as significant.[27] Further exploration and analysis are required to unravel the complex relationship that exists among quantitative gait data, clinical observation and patient perception of the prosthesis.[75] The inability to detect changes between prosthetic configurations using quantitative gait analysis is not a limitation of current motion measurement systems; they are able to measure body motion and forces with sufficient accuracy. The problems we are currently struggling with concern our lack of understanding about how to best restore ambulation ability in someone with a leg amputation, how to provide sufficient function through prosthetic design and with appropriate selection of componentry, and how to best use and incorporate quantitative gait data with visual observation and subjective feedback to effect substantive improvement in the function, aesthetics, and efficiency of prosthetic gait.

Quantitative gait analysis is recognized as being useful for providing an objective assessment about the way a person walks. Studies of prosthetic users reported in the literature tend to indicate a lack of consistency in quantitative gait measures, even in similar populations of amputee subjects who are walking with comparable prosthetic configurations. Therefore, the value of using these data individually for outcome measures is questionable. Energy expenditure measures, as a gross indicator of walking performance, tend to show some promise as reliable outcome measures for the evaluation of prosthetic gait, though it is not possible to readily identify specific gait abnormalities that may be evident in temporal-spatial, kinematic or kinetic data. For the time being, quantitative gait analysis may be best used in the research laboratory as opposed to the clinic, but it is important that we continue to strive to effectively integrate these measurements with the experience and skill of the prosthetist and the subjective feedback of the prosthetic user.

REFERENCES

1. Gage JR, Hicks R. Gait analysis in prosthetics. *J Gerontol* 1985; 39:662–666.
2. Radcliffe C. Functional considerations in the fitting of above-knee prostheses. In: Wilson AB, ed. *Selected Articles from Artificial Limbs*. Huntington, NY: Robert E. Krieger Publishing Co. Inc.;1970:5–30.
3. Edelstein JE. Prosthetic and orthotic gait. In: Smidt GL, ed. *Gait in Rehabilitation*. New York: Churchill Livingston Inc.;1990: 281–300.
4. Saleh M. Alignment and gait optimization in lower-limb amputees. In: Murdoch, G, Donovan RG, eds. *Amputation Surgery & Lower Limb Prosthetics*. Oxford: Blackwell Scientific Publications;1988:357-366.
5. Kleissen RFM. Factors in clinical application of gait analysis. *J Rehabil Sci* 1990;3:106–109.
6. Murray MP. Gait as a total pattern of movement. *Am J Phys Med* 1967;46:290–333.
7. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res* 1990;8:383–392.
8. Miff SC. *Gait initiation and termination in non-disabled ambulators and in people with unilateral lower limb loss*. [Thesis]. Evanston, IL: Northwestern University, 2004.
9. Winter DA, Sienko SE. Biomechanics of below-knee amputee gait. *J Biomech* 1988;21:361–367.
10. Gard SA, Konz RJ. The effect of a shock-absorbing pylon on the gait of persons with unilateral transtibial amputation. *J Rehabil Res Dev* 2003;40:109–124.
11. James U, Oberg K. Prosthetic gait pattern in unilateral above-knee amputees. *Scand J Rehabil Med* 1973;5:35–50.
12. Murray MP, Sepic SB, Gardner GM, Mollinger LA. Gait patterns of above-knee amputees using constant friction knee components. *Bull Prosthet Res* 1980;17:35–45.
13. Boonstra AM, Fidler V, Eisma WH. Walking speed of normal subjects and amputees: aspects of validity of gait analysis. *Prosthet Orthot Int* 1993;17:78–82.
14. Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech* 1977;10: 261–268.
15. Murray MP, Drought AB, Kory RC. Walking Patterns of Normal Men. *J Bone Joint Surg Am* 1964;46:335–360.
16. Inman VT, Ralston HJ, Todd F. *Human Walking*, Baltimore, MD: Williams & Wilkins; 1981.

17. Hermodsson Y, Ekdahl C, Persson BM, Roxendal G. Gait in male trans-tibial amputees: a comparative study with healthy subjects in relation to walking speed. *Prosthet Orthot Int* 1994;18:68–77.

18. Drillis R. Objective recording and biomechanics of pathological gait. *Ann N Y Acad Sci* 1958;74:86–109.

19. Gauthier-Gagnon C, Gravel D, St-Amand H, et al. Changes in ground reaction forces during prosthetic training of people with transfemoral amputations: a pilot study. *J Prosthet Orthot* 2000; 12:72–77.

20. Jaegers SM, Arendzen JH, de Jongh HJ. Prosthetic gait of unilateral transfemoral amputees: a kinematic study. *Arch Phys Med Rehabil* 1995;76:736–743.

21. Barth DG, Schumacher L, Sienko-Thomas S. Gait analysis and energy cost of below-knee amputees wearing six different prosthetic feet. *J Prosthet Orthot* 1992;4:63–75.

22. Hannah RE, Morrison JB, Chapman AE. Prostheses alignment: effect on gait of persons with below-knee amputations. *Arch Phys Med Rehabil* 1984;65:159–162.

23. Nielsen DH, Shurr DG, Golden JC, Meier KG. Comparison of energy cost and gait efficiency during ambulation in below-knee amputees using different prosthetic feet: a preliminary report. *J Prosthet Orthot* 1989;1:24–31.

24. Macfarlane PA, Nielsen DH, Shurr DG, et al. Transfemoral amputee physiological requirements: comparisons between SACH foot walking and Flex-foot walking. *J Prosthet Orthot* 1997;9:138–143.

25. Lehmann JF, Price R, Boswell-Bessette S, et al. Comprehensive analysis of dynamic elastic response feet: Seattle Ankle/Lite Foot versus SACH foot. *Arch Phys Med Rehabil* 1993;74:853–861.

26. Perry J, Boyd LA, Rao SS, Mulroy SJ. Prosthetic weight acceptance mechanics in transtibial amputees wearing the Single Axis, Seattle Lite, and Flex Foot. *IEEE Trans Rehabil Eng* 1997;5:283–289.

27. Torburn L, Perry J, Ayyappa E, Shanfield SL. Below-knee amputee gait with dynamic elastic response prosthetic feet: a pilot study. *J Rehabil Res Dev* 1990;27:369–384.

28. Snyder RD, Powers CM, Fontaine C, Perry J. The effect of five prosthetic feet on the gait and loading of the sound limb in dysvascular below-knee amputees. *J Rehabil Res Dev* 1995;32: 309–315.

29. Godfrey CM, Jousse AT, Brett R, Butler JF. A comparison of some gait characteristics with six knee joints. *Orthot Prosthet* 1975;29:33–38.

30. Murray MP, Mollinger LA, Sepic SB, et al. Gait patterns in above-knee amputee patients: hydraulic swing control vs constant-friction knee components. *Arch Phys Med Rehabil* 1983;64:339–345.

31. Boonstra AM, Schrama J, Fidler V, Eisma WH. Energy cost during ambulation in transfemoral amputees: a knee joint with a mechanical swing phase control vs a knee joint with a pneumatic swing phase control. *Scand J Rehabil Med* 1995;27:77–81.

32. Isakov E, Susak Z, Becker E. Energy expenditure and cardiac response in above-knee amputees while using prostheses with open and locked knee mechanisms. *Scand J Rehabil Med Suppl* 1985;12:108–111.

33. Gitter A, Czerniecki JM, DeGroot DM. Biomechanical analysis of the influence of prosthetic feet on below-knee amputee walking. *Am J Phys Med Rehabil* 1991;70:142–148.

34. Breakey JW. Gait of unilateral below-knee amputees. *Orthot Prosthet* 1976;30:17–24.

35. Lewallen R, Quanbury AO, Ross K, Letts R. *A biomechanical study of normal and amputee gait*, Champaign, Illinois: Human Kinetics Publishers; 1985.

36. Zuniga EN, Leavitt LA, Calvert JC, et al. Gait patterns in above-knee amputees. *Arch Phys Med Rehabil* 1972;53:373–382.

37. Judge GW, Fisher L. A bouncy knee for above-knee amputees. *Eng Med* 1981;10:27–31.

38. Blumentritt S, Scherer HW, Wellershaus U, Michael JW. Design principles, biomechanical data and clinical experience with a polycentric knee offering controlled stance phase knee flexion: a preliminary report. *J Prosthet Orthot* 1997;9:18–24.

39. Koehler SR, Gard SA, Meier MR, et al. Stance-phase knee flexion in persons with unilateral transfemoral amputations walking on an Otto Bock 3R60 EBS Knee: A preliminary report. Paper presented at the 9th Annual Meeting of the Gait and Clinical Movement Analysis Society (GCMAS), Lexington, KY, April 21–24, 2004.

40. Michaud SB, Gard SA, Childress DS. A preliminary investigation of pelvic obliquity patterns during gait in persons with transtibial and transfemoral amputation. *J Rehabil Res Dev* 2000; 37:1–10.

41. Song KM, Halliday SE, Little DG. The effect of limb-length discrepancy on gait. *J Bone Joint Surg Am* 1997;79:1690–1698.

42. Cappozzo A, Figura F, Gazzani F, et al. Angular displacements in the upper body of AK amputees during level walking. *Prosthet Orthot Int* 1982;6:131–138.

43. Lewallen R, Dyck G, Quanbury A, et al. Gait kinematics in below-knee child amputees: a force plate analysis. *J Pediatr Orthop* 1986;6:291–298.

44. Engsberg JR, Lee AG, Patterson JL, Harder JA. External loading comparisons between able-bodied and below-knee-amputee children during walking. *Arch Phys Med Rehabil* 1991;72: 657–661.

45. Michaud SB. *Prosthetic vs. standard walking: Quantitative observations*. [Thesis] Evanston, IL: Northwestern University, 1997.

46. Pinzur MS, Smith D, Tornow D, et al. Gait analysis of dysvascular below-knee and contralateral through-knee bilateral amputees: a preliminary report. *Orthopedics* 1993;16:875–879.

47. Mooney J, Hill S, Supan TJ, Barth DG. Comparison of floor reaction and rotational forces in the gait of a transtibial amputee using a Re-Flex VSP Flex Foot design: A pilot study. Paper presented at the 21st Annual Meeting & Scientific Symposium of the AAOP, New Orleans, LA, March 21–25, 1995.

48. Miller LA, Childress DS. Analysis of a vertical compliance prosthetic foot. *J Rehabil Res Dev* 1997;34:52–57.

49. Arya AP, Lees A, Nirula HC, Klenerman L. A biomechanical comparison of the SACH, Seattle and Jaipur feet using ground reaction forces. *Prosthet Orthot Int* 1995;19:37–45.

50. Murray D, Hartvikson W, Anton H, et al. With a spring in one's step. *Clin Prosthet Orthot* 1988;12:128–135.

51. Powers CM, Torburn L, Perry J, Ayyappa E. Influence of prosthetic foot design on sound limb loading in adults with unilateral below-knee amputations. *Arch Phys Med Rehabil* 1994;75: 825–829.

52. Czerniecki JM, Gitter AJ. Gait analysis in the amputee: has it helped the amputee or contributed to the development of improved prosthetic components? *Gait Posture* 1996;4:258–268.

53. van der Linden ML, Solomonidis SE, Spence WD, et al. A methodology for studying the effects of various types of prosthetic feet on the biomechanics of trans-femoral amputee gait. *J Biomech* 1999;32:877–889.

54. Underwood HA, Tokuno CD, Eng JJ. A comparison of two prosthetic feet on the multi-joint and multi-plane kinetic gait compensations in individuals with a unilateral trans-tibial amputation. *Clin Biomech (Bristol, Avon)* 2004;19:609–616.

55. Czerniecki JM, Gitter A, Munro C. Joint moment and muscle power output characteristics of below knee amputees during running: the influence of energy storing prosthetic feet. *J Biomech* 1991;24:63–75.

56. Macfarlane PA, Nielsen DH, Shurr DG. Mechanical gait analysis of transfemoral amputees: SACH Foot versus the Flex-foot. *J Prosthet Orthot* 1997;9:144–151.

57. Postema K, Hermens HJ, de Vries J, et al. Energy storage and release of prosthetic feet, I: biomechanical analysis related to user benefits. *Prosthet Orthot Int* 1997;21:17–27.

58. Sadeghi H, Allard P, Duhaime PM. Muscle power compensatory mechanisms in below-knee amputee gait. *Am J Phys Med Rehabil* 2001;80:25–32.

59. Saunders JB, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. *J Bone Joint Surg* 1953;35A: 543–558.

60. Grieve DW. Gait patterns and the speed of walking. *Bio-Med Engr* 1968;3:119–122.

61. Waters RL, Yakura JS. The energy expenditure of normal and pathologic gait. *Crit Rev Phys Rehab Med* 1989;1:183–209.

62. James U. Oxygen uptake and heart rate during prosthetic walking in healthy male unilateral above-knee amputees. *Scand J Rehabil Med* 1973;5:71–80.

63. Waters RL, Perry J, Antonelli D, Hislop H. Energy cost of walking of amputees: the influence of level of amputation. *J Bone Joint Surg Am* 1976;58:42–46.

64. Jaegers SM, Vos LD, Rispens P, Hof AL. The relationship between comfortable and most metabolically efficient walking speed in persons with unilateral above-knee amputation. *Arch Phys Med Rehabil* 1993;74:521–525.

65. Gailey RS, Wenger MA, Raya M, et al. Energy expenditure of trans-tibial amputees during ambulation at self-selected pace. *Prosthet Orthot Int* 1994;18:84–91.

66. Huang CT, Jackson JR, Moore NB, et al. Amputation: energy cost of ambulation. *Arch Phys Med Rehabil* 1979;60:18–24.

67. Gonzalez EG, Corcoran PJ, Reyes RL. Energy expenditure in below-knee amputees: correlation with stump length. *Arch Phys Med Rehabil* 1974;55:111–119.

68. Schneider K, Hart T, Zernicke RF, et al. Dynamics of below-knee child amputee gait: SACH foot versus Flex foot. *J Biomech* 1993;26:1191–1204.

69. Torburn L, Powers CM, Guiterrez R, Perry J. Energy expenditure during ambulation in dysvascular and traumatic below-knee amputees: a comparison of five prosthetic feet. *J Rehabil Res Dev* 1995;32:111–119.

70. Hsu MJ, Nielsen DH, Yack HJ, Shurr DG. Physiological measurements of walking and running in people with transtibial amputations with 3 different prostheses. *J Orthop Sports Phys Ther* 1999;29:526–533.

71. Buckley JG, Jones SF, Birch KM. Oxygen consumption during ambulation: comparison of using a prosthesis fitted with and without a tele-torsion device. *Arch Phys Med Rehabil* 2002;83: 576–580.

72. Gailey RS, Lawrence D, Burditt C, et al. The CAT-CAM socket and quadrilateral socket: a comparison of energy cost during ambulation. *Prosthet Orthot Int* 1993;17:95–100.

73. Flandry F, Beskin J, Chambers RB, et al. The effect of the CAT-CAM above-knee prosthesis on functional rehabilitation. *Clin Orthop* 1989;:249–262.

74. Traugh GH, Corcoran PJ, Reyes RL. Energy expenditure of ambulation in patients with above-knee amputations. *Arch Phys Med Rehabil* 1975;56:67–71.

75. Hafner BJ, Sanders JE, Czerniecki J, Fergason J. Energy storage and return prostheses: does patient perception correlate with biomechanical analysis? *Clin Biomech (Bristol, Avon)* 2002;17: 325–344.