Residual limb volume change: Systematic review of measurement and management

Joan E. Sanders, PhD; Stefania Fatone, PhD

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Background: Management of residual limb volume affects decisions regarding timing of fit of the first prosthesis, when a new prosthetic socket is needed, design of a prosthetic socket, and prescription of accommodation strategies for daily volume fluctuations.

Objectives: This systematic review assesses what is known about measurement and management of residual limb volume change in persons with lower-limb amputation.

Criteria for selecting studies for this review:

Types of studies: Table 1,2,3

Types of participants: Lower limb amputation

Types of interventions: Group I: descriptions of residual limb volume measurement techniques; group II: studies investigating the effect of residual limb volume change on clinical care in people with lower-limb amputation; and group III: studies of residual limb volume management techniques or descriptions of techniques for accommodating or controlling residual limb volume.

Types of outcome measures: Table 1,2,3

Search strategy for identification of studies:

Conclusion: Overall, limited evidence exists regarding the management of residual limb volume, and the evidence available focuses primarily on adults with transtibial amputation in the early postoperative phase. While we can draw some insights from the available research about residual limb volume measurement and management, further research is required.

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Table 1.
Summary of residual limb volume measurement techniques (group I articles).

Technique/Study	Distortion Because Device Contacted Residuum?	Noninstantaneous (>5 s) Measurement? (scan time) (s)	Error from Subject Movement?	Spatial Error (mm)	Volume Change Error (on limb replicas or subjects with amputation) (%)	Shapes and Tests Used
Water Displacement						
Fernie et al. [1]	O	X	X	NA	1.0	Limb replicas, repeatability error
Starr [2]	O	X	X	NA	1.5	Limb replicas, repeatability error
Casting + Water Displacement						
Commean et al. [3]	X	X	O	NA	0.3	Limb replicas, repeatability error
Anthropometric Measurement						
Krouskop et al. [4]	X	X	O	NR	0.0 ± 4.7	Limb replicas, compared with water displacement
Boonhong [5]	X	X	O	NR	NR	Subjects with amputation
Boonhong [6]	X	X	O	NR	2.4 to 5.7	Subjects with amputation, compared with water displacement
Contact Probes						
Krouskop et al. [7]	X	X	X	NG	−6.2 ± 8.9	Subjects with amputation, compared with water displacement
Vannah et al. [8]	X	X (90)	X	typ < 1.0	NR	Cylindrical model, compared with actual shape
McGarry & McHugh [9]	X	X	X	typ < 1.0, up to 4.3	NR	Cylindrical model
McGarry & McHugh [10]	X	X	X	typ < 1.0, up to 4.3	NR	Cylindrical model
McGarry et al. [11]	X	X	X	up to 8.3	3.7 up to 10.5	Limb replicas, compared with high-resolution instrument
Optical Silhouetting						
Schreiner & Sanders [12]	O	O (1.1)	X	0.5	NR	Cylindrical model
Sanders & Lee [13]	O	O (1.5)	O	0.2	0.1; 0.6/1.0	Limb replica, repeatability error; limb replica repeatability error with movement and with/without correction algorithm
Optical Fringe Projection						
Commean et al. [3]	O	O (<1.0)	X	0.6	0.6	Limb replicas, repeatability error
Commean et al. [14]	O	O (<1.0)	X	0.6	NG	Limb replicas, repeatability error
Ultrasound						
He et al. [15]	O	X (780)	X	1.5	NR	Cylindrical model
He et al. [16]	O	X (780)	X	1.5	NR	Cylindrical model
SXCT						
Smith et al. [17]	O	X (32)	X	NR	2.0	Cadaver leg phantom, compared with water

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Smith et al. [18]	O	X (32)	X	NR	<1.0	Limb replicas, repeatability error
Smith et al. [19]	O	X (32)	X	NR	<1.0	Subjects with amputation, repeatability error
Commean et al. [3]	O	X (32)	X	0.6	0.6	Limb replicas, repeatability error
Commean et al. [20]	O	X (32)	O	1.0	NG	Markers placed on subjects with amputation, repeatability error
Laser Scanning						
Fernie et al. [21]	O	O (0.6)	X	NG	NG	No evaluation reported
Oberg et al. [22]	O	X (10)	X	NG	NG	No evaluation reported
Lilja & Oberg [23]	O	X (10)	X	NG	2.5; 0.5	Limb replicas, compared with casting + water displacement; limb replicas, repeatability error
Johansson & Oberg [24]	O	X (10)	X	NG	0.3; 0.4	Limb replicas, compared with casting + water displacement; limb replicas, repeatability error
MRI						
Buis et al. [25]	O	X (592)	O	0.6	NG	Subjects with amputation, compared with displacement gauge and MRI system resolution
Bioimpedance						
Sanders et al. [26]	O	O (<1.0)	O	NA	0.2	Nondisabled subjects, repeatability during standing

1. Fernie GR, Holliday PJ, Lobb RJ. An instrument for monitoring stump oedema and shrinkage in amputees. Prosthet Orthot Int. 1978;2(2):69–72. [PMID: 364403] DOI:10.3109/03093647809177770
2. Starr TW. A computerized device for the volumetric analysis of the residual limbs of amputees. Bull Prosthet Res. 1980;10–33:98–102. [PMID: 7236952]
3. Commean PK, Smith KE, Cheverud JM, Vannier MW. Precision of surface measurements for below knee residua. Arch Phys Med Rehabil. 1996;77(5):477–86. [PMID: 8629925] DOI:10.1016/S0003-9993(96)90037-4
4. Krouskop TA, Yalcinkaya M, Muilenberg AL, Holland KC, Zuniga EN. A measurement technique to assess residual limb volume. Orthop Rev. 1979;8:69–77.
5. Boonhong J. Correlation between volumes and circumferences of residual limb in below knee amputees. J Med Assoc Thai. 2006;89(Suppl 3):S1–4. [PMID: 17722302]
6. Boonhong J. Validity and reliability of girth measurement (circumference measurement) for calculating residual limb volume in below-knee amputees. Chula Med J. 2007;51:77–88.
7. Krouskop TA, Dougherty D, Yalcinkaya MI, Muilenberg A. Measuring the shape and volume of an above-knee stump. Prosthet Orthot Int. 1988;12(3):136–42. [PMID: 3217243]
8. Vannah W, Drvaric DM, Stand JA, Hastings JA, Slocum JE, Harning DM, Gorton GE. Performance of a continuously sampling hand-held digitizer for residual-limb shape measurement. J Prosthet Orthot. 1997;9(4):157–62. DOI:10.1097/00008526-199700940-00006
9. McGarry T, McHugh B. Evaluation of a contemporary CAD/CAM system. Prosthet Orthot Int. 2005;29(3):221–29. [PMID: 16466152] DOI:10.1080/03093640500199497
10. McGarry T, McHugh B. Comparison of the results of four users of a contemporary CAD/CAM system. Prosthet Orthot Int. 2007;31(1):27–35. [PMID: 17365882] DOI:10.1080/03093640600942101
11. McGarry T, McHugh B, Buis A, McKay G. Evaluation of the effect of shape on a contemporary CAD system. Prosthet Orthot Int. 2008;32(2):145–54. [PMID: 18569882]

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Table 1. (cont)

Summary of residual limb volume measurement techniques (group I articles).

12. Schreiner RE, Sanders JE. A silhouetting shape sensor for the residual limb of a below-knee amputee. IEEE Trans Rehabil Eng. 1995;3(3): 242–53. DOI:10.1109/86.413197
13. Sanders JE, Lee GS. A means to accommodate residual limb movement during optical scanning: A technical note. IEEE Trans Neural Sys Rehabil Eng. 2008;16(5):505–9. [PMID: 18990654] DOI:10.1109/TNSRE.2008.2003388
14. Commean PK, Smith KE, Vannier MW. Design of a 3-D surface scanner for lower limb prosthetics: A technical note. J Rehabil Res Dev. 1996;33(3):267–78. [PMID: 8823674]
15. He P, Xue K, Chen Q, Murka P, Schall S. A PC-based ultrasonic data acquisition system for computer-aided prosthetic socket design. IEEE Trans Rehabil Eng. 1996;4(2):114–19. [PMID: 8798078] DOI:10.1109/86.506408
16. He P, Xue K, Murka P. 3-D imaging of residual limbs using ultrasound. J Rehabil Res Dev. 1997;34(3):269–78. [PMID: 9239619]
17. Smith KE, Vannier MW, Commean PK. Spiral CT volumetry for below-knee residua. IEEE Trans Rehabil Eng. 1995;3(3):235–41. DOI:10.1109/86.413196
18. Smith KE, Commean PK, Bhatia G, Vannier MW. Validation of spiral CT and optical surface scanning for lower limb stump volumetry. Prosthet Orthot Int. 1995;19:97–107.
19. Smith KE, Commean PK, Vannier MW. Residual-limb shape change: Three-dimensional CT scan measurement and depiction in vivo. Radiology. 1996;200(3): 843–50. [PMID: 8756942]
20. Commean PK, Brunsden BS, Smith KE, Vannier MW. Below-knee residual limb shape change measurement and visualization. Arch Phys Med Rehabil. 1998; 79(7):772–82. [PMID: 9685090] DOI:10.1016/S0003-9993(98)90355-0
21. Fernie GR, Griggs G, Bartlett S, Lunau K. Shape sensing for computer aided below-knee prosthetic socket design. Prosthet Orthot Int. 1985;9(1):12–16. [PMID: 4000905]
22. Oberg K, Kofman J, Karisson A, Lindstrom B, Siglad G. The CAPOD system—A Scandinavian CAD/CAM system for prosthetic sockets. J Prosthet Orthot. 1989;1(3):139–48. DOI:10.1097/00008526-198904000-00008
23. Lilja M, Oberg T. Volumetric determinations with CAD/CAM in prosthetics and orthotics: Errors of measurement. J Rehabil Res Dev. 1995;32(2):141–48. [PMID: 7562654]
24. Johansson S, Oberg T. Accuracy and precision of volumetric determinations using two commercial CAD systems for prosthetics: A technical note. J Rehabil Res Dev. 1998;35(1):27–33. [PMID: 9505250]
25. Buis AW, Condon B, Brennan D, McHugh B, Hadley D. Magnetic resonance imaging technology in transtibial socket research: A pilot study. J Rehabil Res Dev. 2006;43(7):883–90. [PMID: 17436174] DOI:10.1682/JRRD.2005.08.0145
26. Sanders JE, Rogers EL, Abrahamson DC. Assessment of residual-limb volume change using bioimpedence. J Rehabil Res Dev. 2007;44(4):525–36. [PMID: 18247249] DOI:10.1682/JRRD.2006.08.0096

MRI = magnetic resonance imaging, NA = not applicable, NG = not given, NR = not relevant because testing was conducted on cylindrical model, O = not present, SXCT = spiral X-ray computer tomography, typ = typically, X = present.

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Table 2.
Summary of articles included in groups II and III.

Author	Group	Measurement Method	Study Design*	Internal Validity	External Validity	Additional Category
Goldberg et al. [1]	III	Water Displacement	E5	Low	Low	Early limbs, whirlpool therapy
Manella [2]	III	Anthropometric	E1	Moderate	High	Early limbs, shrinker sock vs EB
Fernie & Holliday [3]	II	Water Displacement	O1	Moderate	Moderate	Early and mature limbs
Mueller [4]	III	Anthropometric	E1	Moderate	Moderate	Early limbs, RRD vs EB
Liedberg et al. [5]	II & III	Anthropometric	E1	Low	Low	Early limbs, adaptable device
Persson & Liedberg [6]	II	Anthropometric	O5	Low	Moderate	Early limbs
Wilson et al. [7]	III	NA	X2	NA	NA	Adaptable device
Golbranson et al. [8]	II	Anthropometric Water Displacement	E2	Low	Moderate	Correlated measurement techniques in early limbs
Pinzur et al. [9]	III	NA	X2	NA	NA	Adaptable device
MacLean & Fick [10]	II & III	Anthropometric	E2	Moderate	High	Early limbs, SRD vs EB
Lilja & Oberg [11]	II	Laser Scan	O5	Low	High	Early limbs
Lilja et al. [12]	II	MRI	O6	Low	High	Early limbs
Lilja et al. [13]	II	Laser Scan	O5	Moderate	Moderate	Early limbs
Wong & Edelstein [14]	II & III	Anthropometric	E1	Moderate	High	Early limbs, SRD vs EB
Board et al. [15]	III	Casting + Water Displacement	E5	Low	Moderate	Mature limbs, vacuum-assisted suspension
Goswami et al. [16]	III	Casting + Water Displacement	E5	Low	Moderate	Mature limbs, vacuum-assisted suspension
Graf & Freijah [17]	III	Casting + Water Fill/ Displacement	E1	Moderate	High	Early limbs, RRD vs RRD + gel sock
Greenwald et al. [18]	III	Fluid-Filled Bladders	O6	Low	Low	Adaptable device
Zachariah et al. [19]	II	Optical Scan	O5	High	High	Mature limbs
Nawijn et al. [20]	III	NA	S2	NA	NA	Systematic review
Sanders et al. [21]	II	Optical Scan	O5	Moderate	High	Mature limbs
Sanders et al. [22]	III	Fluid-Filled Bladders	O6	High	High	Adaptable device
Singh et al. [23]	II	Ultrasound	O1	Moderate	High	Early limbs
Janchai et al. [24]	III	Anthropometric	E1	Moderate	High	Early limbs, RRD vs EB
Ogawa et al. [25]	III	Fluid-Filled Bladders	O6	Low	Low	Adaptable device
Sanders et al. [26]	I & II	Bioimpedance	O5	High	High	Mature limbs

*Refer to **Appendix 1** (available online only) and Hafner [27] for study design descriptors.

1. Goldberg MJ, Culver JV, Carson JF. Volume changes in below-knee amputation stumps as affected by type of whirpool-tank hydrotherapy. J Am Gerontol Soc. 1968;16(1):101–105. [PMID: 5634466]
2. Manella KJ. Comparing the effectiveness of elastic bandages and shrinker socks for lower extremity amputees. Phys Ther. 1981;61(3):334–37. [PMID: 7465627]
3. Fernie GR, Holliday PJ. Volume fluctuations in the residual limbs of lower limb amputees. Arch Phys Med Rehabil. 1982;63(4):162–65. [PMID: 7082139]
4. Mueller MJ. Comparison of removable rigid dressings and elastic bandages in preprosthetic management of patients with below-knee amputations. Phys Ther. 1982;62(10):1438–41. [PMID: 7122702]
5. Liedberg E, Hommerberg H, Persson BM. Tolerance of early walking with total contact among below-knee amputees—A randomized test. Prosthet Orthot Int. 1983;7(2):91–95. [PMID: 6622240]
6. Persson BM, Liedberg E. A clinical standard of stump measurement and classification in lower limb amputees. Prosthet Orthot Int. 1983;7(1):17–24. [PMID: 6856447]
7. Wilson AB Jr, Schuch CM, Nitschke RO. A variable volume socket for below-knee prostheses. Clin Prosthet Orthot. 1987;11(1):11–19.
8. Golbranson FL, Wirta RW, Kuncir EJ, Lieber RL, Oishi C. Volume changes occurring in postoperative below-knee residual limbs. J Rehabil Res Dev. 1988;25(2):11–18. [PMID: 3361456]
9. Pinzur MS, Angelico JA, Quigley MJ. A volume-adaptable prosthesis for ankle disarticulation. J Prosthet Orthot. 1993;5:77–78. DOI:10.1097/00008526-199307000-00003
10. MacLean N, Fick GH. The effect of semirigid dressings on below-knee amputations. Phys Ther. 1994;74(7):668–73. [PMID: 8016199]
11. Lilja M, Oberg T. Proper time for definitive transtibial prosthetic fitting. J Prosthet Orthot. 1997;9(2):90–95. DOI:10.1097/00008526-199700920-00009
12. Lilja M, Hoffmann P, Oberg T. Morphological changes during early trans-tibial prosthetic fitting. Prosthet Orthot Int. 1998;22(2):115–22. [PMID: 9747995]
13. Lilja M, Johansson S, Oberg T. Relaxed versus activated stump muscles during casting for trans-tibial prostheses. Prosthet Orthot Int. 1999;23(1):13–20. [PMID: 10355639]
14. Wong CK, Edelstein JE. Unna and elastic postoperative dressings: Comparison of their effects on function of adults with amputation and vascular disease. Arch

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Table 2. (cont)
Summary of articles included in groups II and III.

15. Board WJ, Street GM, Caspers C. A comparison of trans-tibial amputee suction and vacuum socket conditions. Prosthet Orthot Int. 2001;25(3):202–9. [PMID: 11860094] DOI:10.1080/03093640108726603
16. Goswami J, Lynn R, Street G, Harlander M. Walking in a vacuum-assisted socket shifts the stump fluid balance. Prosthet Orthot Int. 2003;27(2):107–13. [PMID: 14571940] DOI:10.1080/03093640308726666
17. Graf M, Freijah N. Early trans-tibial oedema control using polymer gel socks. Prosthet Orthot Int. 2003;27(3):221–26. [PMID: 14727703] DOI:10.1080/03093640308726685
18. Greenwald RM, Dean RC, Board WJ. Volume management: Smart Variable Geometry Socket (SVGS) technology for lower-limb prostheses. J Prosthet Orthot. 2003;15(3):107–12. DOI:10.1097/00008526-200307000-00011
19. Zachariah SG, Saxena R, Fergason JR, Sanders JE. Shape and volume change in the transtibial residuum over the short term: Preliminary investigation of six subjects. J Rehabil Res Dev. 2004;41(5):683–94. [PMID: 15558398] DOI:10.1682/JRRD.2003.10.0153
20. Nawijn SE, Van der Linde H, Emmelot CH, Hofstad CJ. Stump management after trans-tibial amputation: A systematic review. Prosthet Orthot Int. 2005;29(1): 13–26. [PMID: 16180374] DOI:10.1080/17461550500066832
21. Sanders JE, Zachariah SG, Jacobsen AK, Fergason JR. Changes in interface pressures and shear stresses over time on trans-tibial amputee subjects ambulating with prosthetic limbs: Comparison of diurnal and six-month differences. J Biomech. 2005;38(8):1566–73. [PMID: 15958212] DOI:10.1016/j.jbiomech.2004.08.008
22. Sanders JE, Jacobsen AK, Fergason JR. Effects of fluid insert volume changes on socket pressures and shear stresses: Case studies from two trans-tibial amputee subjects. Prosthet Orthot Int. 2006;30(3):257–69. [PMID: 17162516] DOI:10.1080/03093640600810266
23. Singh R, Hunter J, Philip A. Fluid collections in amputee stumps: A common phenomenon. Arch Phys Med Rehabil. 2007;88(5):661–63. [PMID: 17466737] DOI:10.1016/j.apmr.2007.02.016
24. Janchai S, Boonhong J, Tiamprasit J. Comparison of removable rigid dressing and elastic bandage in reducing the residual limb volume of below knee amputees. J Med Assoc Thai. 2008;91(9):1441–46. [PMID: 18843876]
25. Ogawa A, Obinata G, Hase K, Dutta A, Nakagawa M. Design of lower limb prosthesis with contact pressure adjustment by MR fluid. Conf Proc IEEE Eng Med Biol Soc. 2008;2008:330–33. [PMID: 19162660]
26. Sanders JE, Harrison DS, Allyn KJ, Myers TR. Clinical utility of in-socket residual limb volume change measurement: Case study results. Prosthet Orthot Int. 2009;33(4):378–90. [PMID: 19961297] DOI:10.3109/03093640903214067
27. Hafner B. American Academy of Orthotists and Prosthetists state-of-the-science evidence reports. The Academy Today. 2008;4(2):A4–A8.

EB = elastic bandage, MRI = magnetic resonance imaging, NA = not applicable, RRD = removable rigid dressing, SRD = semirigid dressing.

Table 3.
Summary of residual limb alignment techniques.

Technique	Study	Application Shapes
Minimization of Volume Differences	Sidles et al. [1]	Residual limbs, sockets
	Smith et al. [2]	Residual limbs, using markers
Anatomical Landmarks	Chahande et al. [3]	Residual limbs
	Jimenez et al. [4]	Residual limbs
Top and Bottom Slice Centroids	Lemaire & Johnson [5]	Sockets
Minimization of Volume Differences and Surface Normals	Zachariah et al. [6]	Residual limbs

1. Sidles JA, Boone DA, Harlan JS, Burgess EM. Rectification maps: A new method for describing residual limb and socket shapes. J Prosthet Orthot. 1989; 1(3):149–53. DOI:10.1097/00008526-198904000-00009
2. Smith KE, Commean PK, Vannier MW. Residual-limb shape change: Three-dimensional CT scan measurement and depiction in vivo. Radiology. 1996; 200(3):843–50. [PMID: 8756942]
3. Chahande A, Billakanti S, Walsh N. Lower limb shape characterization using feature extraction techniques (noncontact laser scanning). Proceedings of the 16th Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 1994 Nov 3–6; Baltimore, MD. Los Alamitos (CA): IEEE; 1994. p. 482–83.
4. Jimenez D, Darm T, Rogers B, Walsh N. Locating anatomical landmarks for prosthetic design using ensemble neural networks. Proceedings of the International Conference on Neural Networks; 1997; Houston, TX. Piscataway (NJ): IEEE; 1997. p. 81–87. Available from: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=611641.
5. Lemaire ED, Johnson F. A quantitative method for comparing and evaluating manual prosthetic socket modifications. IEEE Trans Rehabil Eng. 1996;4(4):303–9. [PMID: 8973956] DOI:10.1109/86.547931
6. Zachariah SG, Sorenson E, Sanders JE. A method for aligning trans-tibial residual limb shapes so as to identify regions of shape change. IEEE Trans Neural Sys Rehabil Eng. 2005;13(4):551–57. [PMID: 16425837] DOI:10.1109/TNSRE.2005.858459