

# Motion-Analysis Studies of Transtibial Prosthesis Users: A Systematic Review

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**Background:** Three-dimensional motion analysis has been used since the beginning of the 1980s to evaluate many aspects of physical function of transtibial amputees. Despite its common use for clinical research, there is large variability in methods of capturing three-dimensional data, description of these methods, reporting of joint kinematics and interpretation of research findings.

**Objectives:** The aim of the following review is to critically examine the specific methodologies used by researchers when collecting three-dimensional kinematic data on transtibial amputees and to provide an overview of the methods used.

**Criteria for selecting studies for this review:**

**Types of studies:** experimental research design, collection of three-dimensional kinematic data of lower-extremity joints, and inclusion of transtibial amputees as experimental subjects.

**Types of participants:** Table 2

**Types of interventions:** Table 2

**Types of outcome measures:** Table 2

**Search strategy for identification of studies:** A literature search was conducted in June 2009 of the Medline, Cinahl and Cochrane databases.

**Conclusion:** The authors recommend that future studies more appropriately address the product name and number of prosthetic components used; how the position of reflective markers on the prosthesis is defined; presentation of data from both sound and affected sides; and definition of the neutral position of the ankle when reporting kinematic data. Where possible, the authors recommend use of a control group.

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**Table 2.** Summary of papers included in the analysis. Variables listed include: quality scores<sup>1</sup> (minimum = 0, maximum = 16; 0 indicating no criterion are fulfilled and 16 indicating all criterion fulfilled), level of evidence based on study design<sup>2</sup> (for further description refer to Table 1), sample size (TT amputees only), mean age of study participants, number of male participants (NA = not available), number of female participants, primary intervention in the study, activity conducted during study (SSWS = Self Selected Walking Speed; CWS = Controlled Walking Speed), number of trials used in analysis, type of foot/feet utilized (in the absence of specific model/manufacture information: SACH = Solid Ankle Cushion Heel, SA = Single-Axis, MA = Multi-Axis, DER = Dynamic Energy Response, ESAR = Energy Storing and Response, CC(2) = Carbon Copy), and stated position of the marker by the author ("not stated" refers to papers in which no specific reference is given to the prosthesis in the body of the article, ie. Helen Hayes, anatomical landmarks, predetermined positions, etc; "estimated matching contralateral" refers to papers where the authors estimate position of markers for the prosthesis from the intact limb), number of markers used, type of markers, biomechanical model defined by author (as detailed as possible, ie. if author stated marker configuration such as Helen Hayes this is stated, when given reference is stated).

Author	Quality	Type	N (amp)	Age	Male	Female	Primary Intervention(s)	Activity	Number of Trials	Type of Feet	Marker Placement	Number of Markers	Type of Markers	Biomechanical Model Defined	Motion Capture System	Capture Frequency
Almusaj, 2009	12	III	16	50.3	10	0	2 foot conditions, 2 alignment conditions	stairs (ascent/descent)	"at least 8"	Proprio-foot	not stated	not stated	passive reflective	"Plug-in Gait" <sup>78</sup>	Vicon	120 Hz
Allard, 1995	6	IV(b)	1	24	1	0	2 foot conditions	level walking, SSWS	3	Space, "symmetrical keel"	not stated	not stated	passive reflective	not stated	Expert Vision	60 Hz
Astrom, 2004	8	IV(a)	7	29	24	5	2 socket conditions	level walking, SSWS (2)	comfortable, 2 fast	Multiflex, Swepro, 1d10, Variflex	not stated	13	passive reflective	not stated	Vicon	50 Hz
Barnett, 2009	6	II(a)	15	53.6	12	3	2 early walking aid (EWA) conditions	level walking (SSWS)	5	not stated	estimated matching contralateral limb	not stated	passive reflective	"6DOF" <sup>82</sup>	Qualisys	100 Hz
Barr, 1992	14	IV(b)	1	33	0	1	2 foot conditions	level walking (SSWS)	10	SACH, CC	estimated matching contralateral limb	9	passive reflective	Defined but not validated	Vicon	50 Hz
Barth, 1992	8	IV(a)	6	51.7	6	0	6 foot conditions	level walking (SSWS)	3	SACH, SAFE2, Seattle Lightfoot, quantum, CC2, flexwalk	not stated	21	passive reflective	not stated	Vicon	not stated
Berge, 2005	13	IV(a)	15	51	15	0	2 prosthesis conditions (pylon)	level walking (SSWS)	10	Seattle Lightfoot	estimated matching contralateral limb	38	passive reflective	"Plug-in Gait"	Vicon	100 Hz
Beyaert, 2008	12	III	17	46	NA	NA	3 Alignment conditions	level walking (SSWS)	3	SACH, Multiflex, Variflex, Sureflex, Flexwalk, Cwalk, Cadence HP, Reflex	estimated matching contralateral	not stated	not stated	"	Vicon	not stated
Centomo, 2008	11	III	7	11	4	3	Investigative	Step-in-place	5	not stated	not stated	24	passive reflective	Defined but not validated (sagittal plane only)	Vicon	60 Hz
Centomo, 2007	14	III	8	12	5	3	Investigative	Step-in-place	5	Seattle Lightfoot	not stated	24	passive reflective	Defined but not validated (sagittal plane only)	Vicon	60 Hz
Chow, 2006	14	IV(a)	6	43	6	1	Alignment conditions, 3 surface conditions	level walking (SSWS), stairs, slope	5	SACH	estimated matching contralateral limb	6	passive reflective	not stated (knee kinematics only)	Vicon	60 Hz
Coiborne, 1992	12	IV(a)	8	13.1	4	4	2 foot conditions	level walking (SSWS)	5	SACH, Seattle	estimated matching contralateral limb	not stated	passive reflective	"4-segment system" <sup>84</sup>	Vicon	not stated
Datta, 2004	9	II(a)	11	47.8	11	0	2 socket conditions	not stated	not stated	Multiflex	not stated	not stated	not stated	"Standard marker set" <sup>75</sup>	Vicon	not stated
Detrembleur, 2005	12	IV(a)	6	50.5	NA	NA	Investigative	level walking (SSWS)	"10 ± 2"	SA, Flexfoot, Variflex, Sureflex	estimated matching contralateral limb	13	passive reflective	"	Elite	50 Hz
Donn, 1989	9	IV(a)	10	NA	9	1	5 mass conditions	level walking (SSWS)	1	SACH, Quantum	estimated matching contralateral limb	10	passive reflective	not stated	Vicon	not stated
Engsberg, 2006	7	IV(b)	1	29	1	0	15 foot conditions, 2 velocity, 2 slope	level walking (CWS (2)), 8 degree slope (up/down)	3	FJ,HF, Greisinger, SAFE, SA, Seattle, STEN, SAFE2, Seattle Light, Quantum, Dynamic, Flexwalk, CC2, SACH	not stated	24	passive reflective	not stated	Motion Analysis Corp.	not stated
Ehara, 1993	9	IV(a)	43	47	36	7	2 socket conditions	level walking (SSWS)	6	not stated	not stated	8	active	not stated	XY-Tracker	50 Hz
Fang, 2007	10	IV(b)	1	NA	1	0	3 alignment conditions	level walking (SSWS)	not stated	SACH	not stated	6	passive reflective	"4-segment model - 2DOF" <sup>86</sup> (Knee only)	Qualisys	180 Hz
Fey, 2009	9	III	14	45	13	1	4 velocity conditions	level walking (CWS (4))	5	"Energy storing", SACH	not stated	36	not stated	not stated (assumed to be 6DOF)	Vicon	120 Hz
Gard, 2003	11	IV(a)	10	54	9	1	2 pylon conditions	level walking, (SSWS (5))	3	College Park, Seattle, CC2, MasterStep	not stated	not stated	passive reflective	"Helen Hayes Model"	Motion Analysis Corp.	120 Hz
Geil, 2000	9	IV(a)	4	36	4	0	Investigative (analysis methods)	level walking (SSWS)	10	Carbon-copy	not stated	15	passive reflective	"Helen Hayes Model"	Vicon	50 Hz
Goh, 1984	7	IV(a)	6	NA	NA	NA	2 foot conditions	level walking (velocity unstated)	5	SACH, SA	not stated	26	passive	not stated	Pailard Bolex	50 Hz
Goujon, 2006	12	III	6	51.5	5	1	Investigative	level walking (SSWS)	10	1C40, 1d10, SACH, Greisinger, Sureflex, Variflex	not stated	46	passive reflective	"Hip location" <sup>89</sup> , "Axis systems" <sup>88</sup> , "Knee joint kinematics" <sup>84</sup>	Vicon	50 Hz
Han, 2003	12	IV(a)	6	41.3	4	2	2 foot conditions (barefoot/shod)	level walking (SSWS)	not stated	SACH, SA	estimated matching contralateral limb	not stated	passive reflective	Foot, Shank + Thigh defined but not validated; Pelvis not defined	Vicon	60 Hz
Hansen, 2006	13	IV(a)	14	46	9	5	3 foot conditions, 3 velocity conditions	level walking, SSWS (Fast, medium, slow)	5	Shape&Roll	estimated matching contralateral limb	not stated	passive reflective	"Modified Helen Hayes" <sup>77</sup>	Motion Analysis Corp.	120 Hz
Hill, 1999	8	IV(a)	7	42.4	6	1	6 obstacle height conditions	obstacle clearance	10	Flexfoot, ReFlex VSP, SeattleLite, SAFE2	not stated	14	passive reflective	"4-link segment model" <sup>80</sup>	Vicon	not stated
Hill, 1997	11	IV(a)	10	36.5	8	2	3 obstacle height conditions	obstacle clearance	10	Flexfoot, ReFlexVSP, SeattleLight, SAFE	not stated	14	passive reflective	Defined but not validated	Vicon	not stated
Hilery, 2000	9	IV(b)	1	24	1	0	3 mass/inertial manipulation	level walking (SSWS)	5	DER	not stated	not stated	passive reflective	not defined	Vicon	50 Hz
Hilery, 1997	6	IV(b)	1	24	1	0	3 mass/inertial manipulation, 2 velocity conditions	level walking (SSWS (2))	5	DER	estimated matching contralateral limb	13	passive reflective	not defined	Vicon	not stated
Jones, 2005	15	III	5	48.9	NA	NA	2 height conditions	step up new level, step down new level	4	Cwalk, SACH, Mercury, Multiflex, SA, Variflex, Dynamic, SeattleLight	estimated matching contralateral	31	passive reflective	"Plug-in Gait" <sup>78</sup>	Vicon	50 Hz
Jones, 2006	14	III	5	48.9	NA	NA	2 height conditions, 2 prosthesis conditions (pylon)	step down new level	2	Cwalk, SACH, Mercury, Multiflex, SA, Variflex, Dynamic, SeattleLight	estimated matching contralateral limb (stated one marker above pylon)	31	passive reflective	"Plug-in Gait"	Vicon	50 Hz
Klute, 2004	9	IV(a)	2	NA	NA	NA	Investigative	level walking (CWS)	10	SeattleLight2	not stated	not stated	not stated	Defined but not validated (sagittal plane only)	Vicon	600 Hz
Lehmann, 1993	12	IV(a)	10	NA	NA	NA	2 foot conditions	level walking (SSWS)	8	SACH, Seattle Ankle	estimated matching contralateral limb	10	passive reflective	not stated	Vicon	not stated

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Lehmann, 1998	11	IV(a)	15	NA	NA	NA	3 mass conditions, 3 mass location conditions	level walking (SSWS), (CWS)	8	not stated	estimated matching contralateral limb	14	passive reflective	Defined but not validated (sagittal plane only)	Vicon	50 Hz
Martinez-Villapando, 2007	6	IV(b)	1	NA	NA	NA	Investigative	level walking (velocity unstated), standing	20	Prototype powered foot/ankle	not stated	9	passive reflective	not stated	Vicon	120 Hz
Miff, 2005	11	III	10	54.1	8	2	3 velocity conditions	level walking (SSWS (3)), gait initiation and termination	3	not stated	not stated	not stated	not stated	"Modified Helen Hayes" <sup>77</sup>	Motion Analysis Corp.	120 Hz
Mouchino, 2006	11	III	5	34	5	0	Investigative	standing, lateral leg lift	10	not stated	not stated	14	passive reflective	Defined but not validated	Elite	100 Hz
Nissan, 1991	6	III	10	NA	10	0	Investigative	level walking, SSWS	3	not stated	not stated	13	passive reflective	not stated	Vicon	50 Hz
Perry, 1993	10	IV(a)	17	NA	NA	NA	5 foot conditions	level walking, (SSWS (2)), stairs, slope	*multiple runs* (not stated)	SACH,CC2,Flexfoot,Seattle,STE N	estimated matching contralateral limb	not stated	passive reflective	not stated	Vicon	50 Hz
Perry, 1997	11	III	10	62.4	10	0	3 foot conditions	level walking (SSWS)	2	SACH,Seattle,Light,Flexfoot	estimated matching contralateral limb	14	passive reflective	"6DOF" <sup>83</sup>	Vicon	50 Hz
Pinzur, 1993	7	IV(a)	4	58	NA	NA	Investigative	level walking (SSWS)	10	SACH	not stated	not stated	not stated	not stated	Watsmart	120 Hz
Postema, 1997	11	II(a)	10	49.2	9	1	4 foot conditions	level walking (SSWS)	10	DynamicPro,MA(OB),Quantum,Layer	not stated	13	passive reflective	not stated	Vicon	50 Hz
Powers, 1994	13	IV(a)	10	49.9	10	0	5 foot conditions	level walking (SSWS)	"3 to 5"	SACH,Quantum,Seattle,CC2,Flexfoot	estimated matching contralateral limb	not stated	passive reflective	not stated	Vicon	not stated
Powers, 1998	10	III	10	62.3	10	0	Investigative	level walking (SSWS)	not stated	SeattleLight	estimated matching contralateral limb	25	passive reflective	"6DOF" <sup>81</sup>	Vicon	50 Hz
Prince, 1993	7	IV(a)	6	19.5	4	2	3 velocity condition	level walking (SSWS), CWS (120%), jogging (2.8m/s)	not stated	Space Foot	estimated matching contralateral limb	10	passive reflective	"4-link segments model" (no reference)	Motion Analysis Corp.	not stated
Quesada, 2000	8	IV(b)	1	36	1	0	2 foot conditions	level walking (SSWS)	"3 or more"	RJFA (prototype), SACH	not stated	not stated	passive reflective	"Modified Helen Hayes" <sup>77</sup>	Vicon	50 Hz
Rao, 1998	12	III	9	61.6	9	0	3 foot conditions	level walking (SSWS)	2	SA, SeattleLight, Flexfoot	estimated matching contralateral limb	not stated	passive reflective	"6DOF" <sup>81</sup>	Vicon	50 Hz
Rogers, 2004	7	IV(a)	2	35	2	0	3 prosthesis conditions (pylon)	golf swing	5	Multiflex	not stated	18	not stated	"18 point model"	Kine Analysis Software	50 Hz
Royer, 2006	9	IV(a)	10	41.2	9	1	Investigative	level walking (SSWS)	3	Flexfoot	estimated matching contralateral limb	27	not stated	"Reduced Cleveland Clinic"	Motion Analysis Corp.	60 Hz
Sadeghi, 2001	9	IV(a)	5	27	5	0	Investigative	level walking (SSWS)	3	SACH	estimated matching contralateral limb	20	passive reflective	"Seven-body segment model" <sup>85</sup>	Motion Analysis Corp.	90 Hz
Schmalz, 2002	9	IV(a)	15	NA	NA	NA	5 foot conditions, 4 alignment conditions	level walking (SSWS)	not stated	1c25,1c71,1d10,1c40,Flexwalk	not stated (Blumenritzi, 1994) estimated "ankle joint" and "toe joint" of prosthesis	not stated	not stated	not stated	Deift Motion Analysis	100 Hz
Schmalz, 2007	10	III	8	51	7	1	2 stair conditions (lead limb)	stairs (ascent/descent)	6	1c25	not stated	8	passive reflective	not stated	Deift Motion Analysis	100 Hz
Schneider, 1993	10	IV(a)	12	10.9	5	7	2 foot conditions, 2 velocity	level walking (SSWS (2))	10	Flexfoot, SACH	estimated matching contralateral limb	12	active	"Lower-limb rigid links" <sup>87</sup>	Watsmart	200 Hz
Selles, 2004a	12	IV(a)	10	44	NA	NA	5 mass conditions	level walking (SSWS)	8	not stated	estimated matching contralateral limb	6	passive reflective	"	Qualisys	50 Hz
Selles, 2004b	11	IV(a)	10	44.2	NA	NA	Investigative	level walking (SSWS)	6	not stated	estimated matching contralateral limb	6	passive reflective	"	Qualisys	50 Hz
Selles, 2003	13	III	10	38	8	2	Investigative	level walking (SSWS)	8	not stated	not stated	not stated	passive reflective	"	Qualisys	50 Hz
Silverman, 2006	10	III	14	45	13	1	4 velocity conditions	level walking (CWS (4))	5	SACH, ESAR	estimated matching contralateral limb	36	passive reflective	not stated (assumed to be 6DOF)	Vicon	120 Hz
Snyder, 1995	11	IV(a)	7	62.1	NA	NA	5 foot conditions	level walking (SSWS)	2	Flexfoot,CC,SeattleLight,Quantum,SACH	estimated matching contralateral limb	not stated	passive reflective	not stated	Vicon	50 Hz
Strike, 2005	10	IV(a)	2	NA	2	0	2 jump conditions (Pros/Unaffected)	jumping (one-legged)	1	SeattleLight, Mercury	estimated	33	passive reflective	"Plug-in Gait" <sup>78</sup>	Vicon	120 Hz
Su, 2008	14	III	19	52.8	14	5	3 velocity conditions	level walking (SSWS (3))	"10 to 15"	Seattle Lightfoot II	not stated	not stated	not stated	"Modified Helen Hayes"	Motion Analysis Corp.	120 Hz
Su, 2007	11	III	19	52.8	NA	NA	3 velocity conditions	level walking (SSWS (3))	"10 to 15"	Seattle Lightfoot II	not stated	not stated	not stated	"Modified Helen Hayes"	Motion Analysis Corp.	120 Hz
Underwood, 2004	11	IV(a)	11	42.5	8	3	2 foot conditions	level walking (SSWS)	5	SAFE, Flexwalk	estimated matching contralateral limb	18	active	"Segment model" <sup>87</sup>	Optotrak	60 Hz
Wagner, 1987	2	IV(a)	6	NA	NA	NA	2 foot conditions	level walking (SSWS)	not stated	SACH, Flexfoot	not stated	not stated	not stated	Vicon	not stated	
Vanicek, 2009	11	III	11	56	9	2	Investigative	level walking (SSWS)	12	Multiflex, Dynamic, Variflex, Cotenus	not stated	28	passive reflective	"6DOF" <sup>82</sup>	Qualisys	100 Hz
Vickers, 2008	11	III	8	71	5	3	2 slope conditions	Slope (ascent/descent)	2	SACH, SA (or perhaps only SACH)	not stated	15	not stated	"73, 77"	Vicon	50 Hz
Viton, 2000	9	III	5	34.8	5	0	2 leg lift conditions	Standing, lateral leg lift	10	not stated	not stated	12	passive reflective	not stated	Elite	100 Hz
Yack, 1999	12	III	5	31.6	5	0	3 foot conditions	stairs (ascent)	"minimum of 3"	Flexfoot, ReFlex VSP, SACH	not stated	not stated	active	"5-segment model" <sup>87</sup>	Optotrak	60 Hz
Zmitrewicz, 2006	11	IV(a)	15	58.1	14	1	2 foot conditions, 2 ankle conditions	level walking (SSWS)	"minimum of 4"	CC2,SACH,MA	estimated matching contralateral limb	15	passive reflective	"Helen Hayes Model"	Vicon	60 Hz
Klute, 2004	9	IV(a)	2	NA	NA	NA	Investigative	level walking (CWS)	10	SeattleLight2	not stated	not stated	not stated	not stated	Vicon	600 Hz
Lehmann, 1993	12	IV(a)	10	NA	NA	NA	2 foot conditions	level walking (SSWS)	8	SACH, Seattle Ankle	estimated matching contralateral limb	10	passive reflective	Defined but not validated (sagittal plane only)	Vicon	not stated