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Evaluation of the subtalar joint during gait using 3-D motion analysis: Does the STJ achieve neutral position?

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Background: One theory of hindfoot biomechanics claims that the subtalar joint (STJ) reaches neutral position during midstance, while another maintains that the STJ stays in an everted position throughout. There is also evidence that STJ position during midstance changes with walking speed. The present study will compare four distinct STJ static positions to 3D kinematics of the STJ during self-selected and fast gait in over-ground level walking.
Methods: The right lower leg of 20 male participants was placed in three clinically used subtalar joint neutral static positions using biomechanical examination: SJNR (STJ neutral by calculation method), SJNP (STJ neutral by palpation method), NCSP (neutral calcaneal stance position), as well as in the resting bilateral standing posture RCSP (resting calcaneal stance position). An eight-camera 3D motion capture system was used to capture and analyze the kinematics of the ankle complex during self-selected and fast walking conditions, as well as, the four static postures.
Results: The 3D subtalar joint movement pattern did not coincide with any of the three subtalar joint neutral positions (SJNR, SJNP and NCSP) during the midstance phase of self-selected or fast walking. Specifically, the subtalar joint remained in a significantly more everted and abducted position with greater deviations from neutral under the fast-walking condition.
Conclusions: None of the clinically used STJ neutral positions agree with the 3D pattern of the STJ during self-selected and fast gait. These results have implications related to clinical practice and the use of the STJ neutral position for evaluation and treatment purposes.

Keywords: subtalar joint, biomechanics, gait

One of the prevailing concepts of STJ function was first advocated by Root [1]. He described his theory of subtalar joint neutral during walking as follows: "Shortly before heel lift, the subtalar joint reaches its neutral position. During the remaining midstance period, the subtalar joint continues to supinate, and the rearfoot moves into a supinated position." The validity of Root's observation of subtalar joint neutral position, however, has been questioned in the biomechanics literature [2]. McPoil and Cornwall published a study in 1994, where they determined the pattern of the rear foot motion on the frontal plane during gait and compared it to the subtalar joint in the neutral position [3]. Contrary to Root's theory, their findings concluded that the neutral position of the rearfoot during stance more closely resembled the

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resting calcaneal stance position than subtalar joint neutral position.

Pierrynowsi et al. questioned the 2-D motion capture used by McPoil and Cornwall as describing the relative rear foot frontal plane motion accurately for only the first 4-36% of the gait cycle, and determined that 3-D motion capture was required to properly assess STJ motion during gait [4]. Pierrynowski et al. improved motion capture methodology and also concluded that the rearfoot did not achieve subtalar neutral position during the stance phase in gait. However, in their study, motion capture of the rearfoot, was taken while subjects walked at a slow speed on treadmill set at 0.89 meters/seconds the same for all subjects. The treadmill as the walking surface seems to affect foot motion during gait and as such it may alter the true rearfoot kinematics during the stance phase of gait [5].

Walking speed itself may also influence STJ position. Tulchin et al [6] findings concluded that when evaluating foot kinematics during gait it was imperative to account or control for walking speed because of the changes that occur with sagittal plane motion in the foot as walking speed increases; namely, an increase in plantarflexion of both the hindfoot and forefoot. Rosenbaum et al [7] showed that with increasing walking speed there was also an increase in pronation. However, both Torburn and later Dubbledam showed that rearfoot motion in the frontal plane was not influenced by walking speed [8,9].

To further understand the function of the STJ during gait, we compared the 3D subtalar position during the midstance phase of gait at self-selected and fast walking speeds on a level walkway to three common clinically used subtalar joint neutral positions and the resting bilateral stance.

MATERIALS AND METHODS

Subjects

Twenty unimpaired, healthy adult male subjects volunteered to participate in the study (age 24.7 ± 1.7 years; mass 79.3 ± 12.0 kg; height 180 ± 7 cm). Inclusion criteria consisted of subjects who were active adults, free from injury over the last year, able to ambulate barefoot without the need for assistive devices, without any lower extremity/foot malalignment or had use of arch supports, shoe pads or foot orthoses. The study was reviewed and approved by the Institutional Review Board.

Experimental protocol

The subtalar joint neutral position is defined in three different ways. Two involve non-weight bearing measurements: one by mathematical calculation and the second by palpation. The third way is in a weight bearing bilateral stance position. In our study, we refer to the non-weightbearing mathematical calculation as SJNR (subtalar joint neutral by range of motion). Root provided a detailed explanation of how to find the subtalar neutral position in the non-weight bearing position which involved establishing the total range of motion for inversion and eversion followed by calculations with a formula he provided which calculated the neutral position as 1/3 of the total range of subtalar joint inversion and eversion from the maximally everted position [10]. The second non-weightbearing STJ neutral position method employs a palpatory technique which we refer to as SJNP (subtalar joint neutral by palpation). This technique was not originally advocated by Root, but instead was adapted and modified over time based on Root's principles. It involves palpating for the congruency of the talar head [11]. This SJNP technique is like that employed by McPoil and Pierrynowski [3, 4]. The third STJ neutral position is weight bearing NCSP (neutral calcaneal stance position). Root described it as follows: with the subject weightbearing in the normal angle and base of gait, the clinician "palpates the congruity of the medial and lateral edges of the talus in relationship to the calcaneus at the subtalar joint", in addition to making sure "the concavity of the lateral surface of the foot is parallel to the concavity on the lateral surface of the leg", and finally that "the lateral surface of the foot describes a straight line in the area of the calcaneocuboid joint" [12]. This technique has been modified over time so that it is most commonly measured by palpating for congruency of the medial and lateral aspects of the talus with the patient standing in the normal angle and base of gait [11]. Root also provided a technique for measuring the frontal plane position of the calcaneus, in the relaxed bilateral stance position, relative to the weightbearing surface which requires one to stand "in normal angle and base of gait" [12]. In the present study, this method is referred to as RCSP (relaxed calcaneal stance position) [See Table 1].

Data collection commenced after obtaining consent from each subject. First a clinical/biomechanical exam was performed on each subject bilaterally. During the clinical/biomechanical exam, subjects' feet were inspected for any visible deformities and standard goniometric measurements were taken for the subtalar joint inversion, eversion range of motion (ROM), as well as the subtalar varus/valgus angle at each of the SJNR, SJNP, NCSP, and RCSP static positions (in random order), using frontal plane bisection lines of the posterior calcaneus and distal shank, according to Root's protocol [10,12]. At the completion of the clinical exam, disposable, adhesive, radiopaque skin markers (2.0 mm pellets) were attached along the bisection line of the calcaneus and distal shank (0.33 mm diameter line), as well as the sustentaculum tali and the peroneal tubercle. Posterior and lateral x-rays were taken, and the relative locations of the radiopaque markers were used along with palpation for accurate skin adhered motion analysis marker placement for better bone alignment representation purposes.

The 3D rear foot joint angles at the four static positions and the average 3D rear foot joint angles over the midstance phase for the two different gait speeds were compared in this study. Two trials for each of the standing (RCSP and NCSP) and prone (SJNR and SJNP) static positions were collected prior to the walking trials. Each static trial captured consisted of three seconds while the positions described above were maintained. The gait speeds were self-selected typical and self-selected fast barefoot walking on a level grade walkway. The subjects were asked to walk first at their preferred typical self-selected speed (SSG) and then at a self-selected faster speed (FWS). Five successful gait trials per speed condition were captured after familiarization with the laboratory environment. A trial was deemed successful if the subject's right foot completely contacted one of the force plates, while the subject did not adjust his step pattern. The average self-selected typical gait speed was 1.27 ± 0.11 m/s, with an average stride length of 1.38 ± 0.09 m, cadence of 109.6 ± 5.8 steps/min, and stance phase duration of 60.9 ± 1.4 % of the gait cycle. The respective gait parameters for the self-selected fast gait were the following: gait speed of 1.70 ± 0.20 m/s, with an average stride length of 1.82 ± 0.12 m, cadence of 124.9 ± 11.1steps/min, and stance phase duration was 58.7 ± 1.7 % of the gait cycle.

The shank (including tibia and fibula) and the calcaneus segments were assumed to be rigid and were tracked in the laboratory reference frame using retro reflective markers (7.9 mm diameter) adhered to the skin at specific anatomical landmarks to construct the respective segmental anatomical reference frames. Specifically: for the shank, markers were placed on the tip of the lateral malleolus (LM), the tip of the medial malleolus (MM), the tip of the fibular head (FH), and the top and bottom of the shank bisection line (TSB) and (BSB), respectively. For the hind foot, markers were placed at the top and bottom of the calcaneus bisection line (TC) and (BC) respectively, the lateral apex of the peroneal tubercle (PT), and the medial apex of the sustentaculum tali (ST). Redundant markers on the shank and calcaneus were placed in the following places for tracking purposes: top and bottom lateral shank (TSL) and (BSL), along the line of the lateral epicondyle of the knee and the lateral malleolus; top and bottom tibia (TT) and (BT) on the medial surface; and the medial and lateral aspect of the calcaneus (MC) and (LC) on a transverse plane passing through the midpoint between TC and BC with the subject standing in the RCSP position. In addition, a toe marker was placed on the second metatarsal head (SMH), which was used as a guide to identify the midpoint between the posterior calcaneus markers TC and BC, at which level the MC and LC were placed, using a laser level during RCSP standing static position. The entire marker set was used for the two standing static positions (RCSP and NCSP), as well as a standing static reference position with the feet at shoulder width apart parallel to each other. The MM, PT and ST markers were removed and were created virtually for the two prone static positions and the dynamic gait captures.

Given the above marker placement, the anatomical reference frames were defined: (1) right shank; the frontal plane was defined by the mid-malleolus point MMP (mid-point between the MM and LM), the LM and the FH; the sagittal plane orthogonal to the frontal, containing the MMP and the mid-shank point MSP (mid-point between the TSB and BSB); the transverse plane for the shank was mutually perpendicular to its frontal and sagittal planes, (2) right hind foot (calcaneus); the sagittal plane was defined using the TC, BC and the midpoint between the MC and LC; the transverse plane orthogonal to the sagittal, containing the midpoints of the TC and BC, and the MC and LC; the frontal plane for the hind foot was mutually perpendicular to its sagittal and transverse planes.

The three-dimensional joint angles of the calcaneus with respect to the shank (representing both the subtalar and the talocrural joints) were calculated using Cardan angles. The sequence of rotations used was sagittal (plantarflexion (-) / dorsiflexion (+)), frontal (eversion (-) / inversion (+)), and then transverse (abduction (-) / adduction (+)) plane [13].

The kinematics data was collected at 120 Hz, using an eight-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA). Ground reaction force data was collected at 1200 Hz using three force plates (AMTI, Watertown, MA) mounted flush with the walking surface and aligned in the direction of walking. A 10 N threshold for the vertical component of the ground reaction force (GRF) was used to determine the stance phase of the gait cycle (heel contact to toe-off).

To remain consistent with Root's theory that "shortly before heel lift, the subtalar joint reaches its neutral position", the midstance phase is operationally defined here as the portion of the stance phase were the foot is flat on the ground from the instant of toe-down to the instant of heel-off. This is consistent with the "Ankle Rocker" definition of Jacquelin Perry where the foot is plantigrade with foot-flat support [14]. The timing of the toe-down and heel-off events were determined using a simple algorithm of threshold crossings of the vertical coordinate of the toe (SMH) and virtual heel (midpoint of TC and BC) markers relative to the average height of these markers during the RCSP static position. Specifically, the toe-down event was identified as the frame following the negative crossing when the vertical coordinate of the SMH marker crossed its respective level of the static RCSP position, and the heel-off event was identified as the frame prior to the positive crossing were the vertical coordinate of the virtual heel marker crossed its respective level plus 3mm higher than the static RCSP position. The plus 3mm level adjustment was needed for consistent event detection to account for the decompression of the heel pad.

One-way repeated measures ANOVA design was used to test for differences in the subtalar joint position across all four static conditions and the mean STJ position during midstance for SSG and FWS gait for each of the 3D planes (at $\alpha < 0.05$). A set of a priori comparisons were performed to test for significant differences in STJ position between gait and each of the 4 static conditions, controlling for Type I error with a Bonferroni adjustment by setting the alpha (α) level to $0.05/4 = 0.0125$. Paired t-test procedures were used to test for subtalar joint position differences between SSG and FWS gait (at $\alpha < 0.05$). The Statistical Package for the Social Sciences (SPSS Version 24.0, Chicago, IL) was used for all data analysis.

RESULTS

The three-dimensional angles of the calcaneus with respect to tibia during the stance phase of gait are shown in Fig. 1. Specifically, the average kinematic curve patterns of an individual subject are shown for the (a) sagittal, (b) frontal, and (c) transverse planes along with his five individual trials during typical self-selected (SSG) walking speed. In the sagittal plane, the three functional arcs are visible starting with the plantarflexion motion of the calcaneus with respect to the tibia approximately until the toes are down (TD). This plantarflexion action is followed by a prolonged dorsiflexion arc where the tibia moves forward on the plantigrade foot, as the load on the foot moves towards the forefoot, and continues this dorsiflexion action beyond heel-off (HO). The final arc is a rapid motion of the calcaneus with respect to the tibia in the plantarflexion direction, probably due to high forces produced by the triceps surae during propulsion.

In the frontal plane, the calcaneus remains in a relatively fixed inverted position until toe-down, followed by an eversion arc while the foot is plantigrade well beyond the heel-off, and during the latter part of the stance we see a rapid relative inversion motion until toe-off.

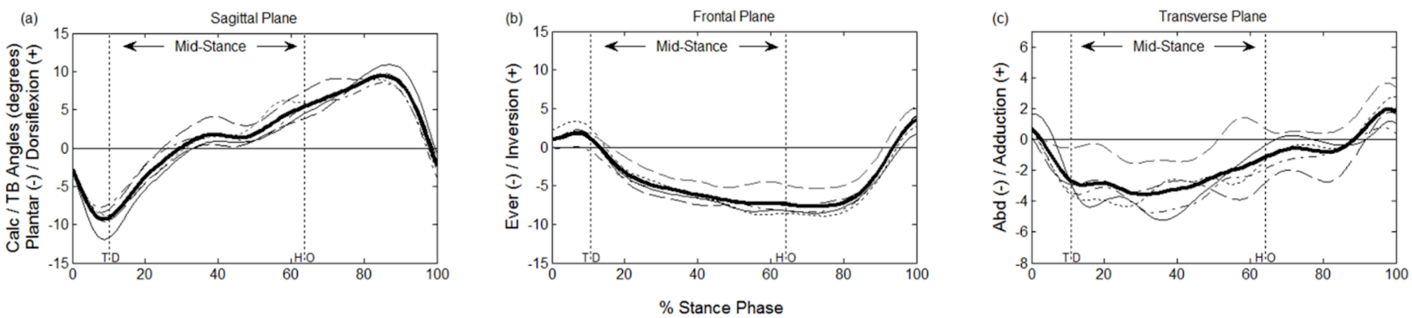

Figure 1 Exemplar single subject temporal profiles (5 trials and mean), of the three dimensional angles of the calcaneus with respect to tibia during stance phase of self-selected speed gait. (a) to (c) represent the sagittal, frontal and transverse planes, respectively. The midstance phase is identified between toe-down (TD) and heel-off (HO). Thin dashed lines denote individual trials (N=5), thick solid line is the average pattern.

The transverse plane motion is characterized by two arcs, a rapid initial abduction until toe-down followed by a gradual prolonged adduction that lasts until toe-off. Overall, there was no difference in the shape of the kinematic curve patterns between trials, subjects, and walking speeds (Figure 1).

The calcaneus to tibia average midstance phase angles show the subtalar joint for the fast gait condition (FWS) in significantly greater dorsiflexion ($p=0.026$) and eversion ($p=0.000$) position relative to the self-selected (SSG) gait condition (Table 2).

The one-way repeated measures ANOVA reveal significant differences in all three planes across all the static positions and the dynamic gait conditions ($p<0.000$). The calcaneus is in a significantly greater inversion (Figure 2) and adduction (Figure 2) position for all three subtalar neutral positions (NCSP, SJNP and SJNR) as related to the average midstance phase position during typical (SSG) and fast walking speed (FWS) gait. The non-weight bearing subtalar neutral joint positions (SJNP and SJNR) place the subtalar joint in a significantly greater plantarflexion position relative to the average subtalar joint position during the midstance phase of both SSG and FWS gait. The weight bearing subtalar neutral position (NCSP) places the subtalar joint in a significantly greater dorsiflexion position relative to the self-selected gait position (Figure 2).

The calcaneus to tibia joint position during the resting calcaneal stance position (RCSP) showed no differences with the average midstance phase position of the subtalar joint during either one of the gait conditions (SSG and FWS) on the sagittal plane (Figure 2). While the calcaneus was found to be everted and adducted with respect to the tibia during the RCSP static position which is consistent with the average midstance phase position during gait, it showed significantly less eversion and adduction angles (Figure 2).

DISCUSSION

In the current study, we compared the average midstance position (toe-down to heel-off) of the STJ to the resting calcaneal stance position and the three STJ neutral positions: calculation by taking 1/3 of the total range of STJ motion from the maximally everted position (SJNR), palpation of the medial and lateral sides of the talar head non-weight bearing (SJNP), and neutral calcaneal stance position (NCSP). Our data showed that the STJ during midstance in gait was everted and abducted relative to these three STJ neutral positions. We also found that eversion and adduction of the calcaneus in relation to the tibia increased during fast walking speed.

The protocol that we followed to measure the movement of the STJ during gait is based on the work of Leardini et al [15] who demonstrated that dynamic foot function is best measured by considering the foot as a multisegment structure, rather than a single, rigid body. Furthermore, Tulchin [6] showed that increased walking speed changes the foot kinematics assessed using a multisegment foot model which led us to the protocol to evaluate the STJ motion during both self-selected and fast-walking gait.

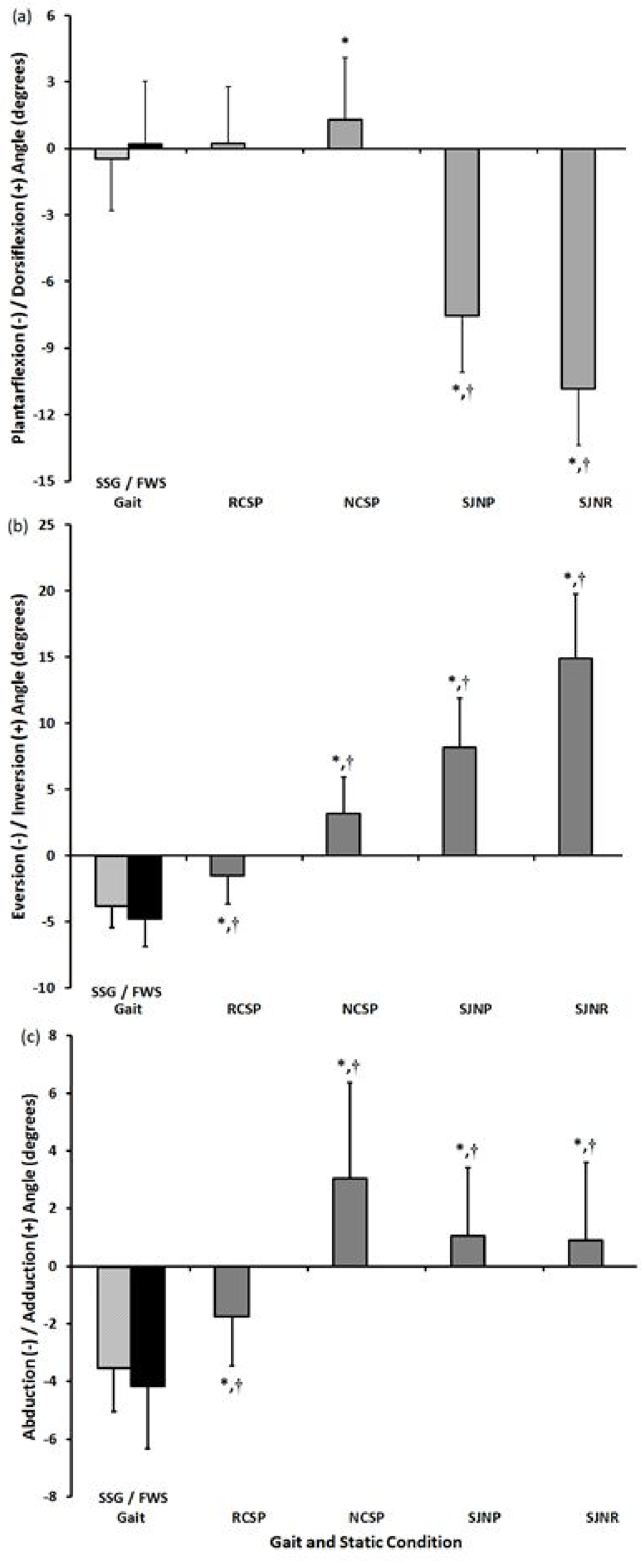

Figure 2 Group means (S.D.) of the calcaneus with respect to tibia angles (º), of the average midstance phase of the self-selected (SSG) and fast walking (FWG) speed gait, and the four static conditions (RCSP, NCSP, SJNP, and SJNR) for: (a) sagittal, (b) frontal, and (c) transverse plane. Bonferroni adjusted significant differences ($p<0.0125$) between SSG and FWG for each of the static conditions are denoted by * and † respectively.

Contrary to Root [1], our data showed that the STJ was in a relative everted throughout the midstance portion of gait, rather than achieving neutral position, in agreement with McPoil [3] and Pierrynowski [4], despite their methodological limitations of 2D analysis and fixed low walking treadmill speed, respectively.

Recently, Buldt et al. [18] showed that clinical static foot postural and mobility measures can explain only a small amount of variation seen in foot kinematics during walking amongst asymptomatic individuals. Their data suggests that the clinical practice measures of foot posture (such as the STJ neutral) and mobility have limited application to foot function during dynamic tasks.

One of the major points of contradiction between the work of Root and others regarding STJ neutral position during gait is probably due to Root's misinterpretation of previously published data. Sobel and Levitz [16] maintain that Root developed his theories of STJ neutral from the work of Wright [17]. In his study, what Wright referred to as the RCSP, Root interpreted as STJ neutral. Whether it was the RCSP or neutral position that was described by Root, our data showed that the actual position of the STJ during gait was everted to both.

Measuring the neutral position of the STJ in a static position has been critical in clinical practice for predicting the "ideal" position of the foot as it functions during gait. Root advocated that STJ neutral was the most stable position of the foot during gait [1], and therefore, foot pathology occurs when there is deviation from this "ideal" neutral position. This applies to the fabrication of foot orthoses, when casts of the feet are taken in either static non-weight bearing or weightbearing STJ neutral position.

While our data showed a significant discrepancy between the static relaxed and the STJ neutral position(s) commonly used in clinical practice against the average dynamic STJ during the midstance phase of gait, there is a substantial concern in the literature related to the lack of STJ neutral position intra- and inter-rater reliability. According to Pierrynowski , experienced practitioners were within ±1° of the subtalar joint non-weight bearing neutral position only 41.3% of the time (within ±3°, 90% of the time)[19]. In Van Gheluwe et al's study, five experienced podiatric physicians showed a high intra-rater reliability when measuring STJ pronation and supination, NCSP, and RCSP but very poor inter-rater reliability except for RCSP [20]. Elveru reviewed the literature concerning the non-weight bearing measurement of subtalar joint neutral position and subtalar joint passive range of motion and concluded that "their reliability is less than optimal [21]." Open and closed kinetic chain measurement of STJ neutral yielded poor intra-rater and inter-rater reliabilities when performed by two inexperienced testers, according to Picciano [22]. Smith-Oricchio found that measurements of calcaneal inversion and eversion and STJ neutral had low to moderate inter-rater reliability [23].

CONCLUSIONS

Our study has shown that the STJ during midstance in gait was more everted and abducted relative to all three STJ neutral positions performed under weightbearing or non-weight bearing conditions. This discrepancy between the STJ position during gait and the STJ neutral positions brings into question the clinical practice use of the STJ neutral position to determine the "ideal" functional position for the foot, as well as its use for orthosis prescription purposes.

Conflict of Interest

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Abbreviation	Definition	Load
RCSP	Relaxed calcaneal stance position	Weight Bearing
NCSP	Neutral calcaneal stance position	Weight Bearing
SJNP	Subtalar joint neutral by palpation	Non-weight Bearing
SJNR	Subtalar joint neutral by range of motion	Non-weight Bearing

Table 1 Abbreviations, definitions and load conditions for the neutral and relaxed subtalar static positions of the foot.

Variable	Self-selected speed gait (SSG)		Fast walking speed gait (FWS)			
	Mean ± SD	95% CI	Mean ± SD	95% CI	*t*	*p*
Sagittal Plane - DF:(+)	-0.44 ± 2.35	-2.66 to 5.29	0.22 ± 2.80	-2.22 to 7.48	2.41	.026
Frontal Plane - IN:(+)	-3.80 ± 1.66	-6.56 to -1.39	-4.80 ± 2.10	-9.57 to -1.95	4.46	.000
Transverse Plane - AD:(+)	-3.51 ± 1.53	-6.31 to -0.75	-4.17 ± 2.17	-8.36 to -1.07	1.99	.061

Table 2 Calcaneus to tibia during midstance (toe down to heel off) average position parameters during gait. Mean, standard deviation, and 95% confidence interval for typical and fast self-selected walking speeds. Differences with walking speed: *t-statistic* and *p* values are shown.

REFERENCES

1. Root ML, Orien WP, Weed JH, et al: "Normal Motion of the Foot and Leg in Gait," in *Biomechanical Examination of the Foot,* Vol 2, p. 127, Clinical Biomechanics Corporation, Los Angeles, 1971.
2. Levitz SJ, Sobel E. The root controversy. Podiatry Management 1997 Sept;16:61-67.
3. McPoil TG , Cornwall MW. Relationship between neutral subtalar joint position and pattern of rearfoot motion during walking. Foot Ankle Int 1994 Mar;15(3):141-145.
4. Pierrynowski MR, Smith SB. Rear foot inversion/eversion during gait relative to the subtalar joint neutral position. Foot Ankle Int 1996 Jul;17(7):406-412.
5. Barton CJ, Kappel SL, Ahrendt P, Simonsen O, Rathleff. Dynamic navicular motion measured using a stretch sensor is different between walking and running, and between over-ground and treadmill conditions. J Foot Ankle Res 2015;8:5.
6. Tulchin K, Orendurff M, Adolfsen S et al. The effects of walking speed on multisegment foot kinematics in adults. J Appl Biomech 2009;25:377-386.
7. Rosenbaum D, Hautmann S, Gold M, Claes L. Effects of walking speed on plantar pressure patterns and hindfoot angular motion. Gait Posture 1994 Sept;2:191-197.
8. Torburn L, Perry J, Gronley J. Assessment of rearfoot motion: passive positioning, one-legged standing, gait. Foot Ankle Int 1998 Oct;19(10):688-693.
9. Dubbledam R, Buurke JH, Simons C, Groothuis-Oudshoorn CGM, Baan H, Nene AV, et al. The effects of walking speed on forefoot, hindfoot, and ankle joint motion. Clin Biomech 2010; 25:796-801.
10. Root ML, Orien WP, Weed JH, et al: "Subtalar Joint," in *Biomechanical Examination of the Foot,* Vol 1, p. 36, Clinical Biomechanics Corporation, Los Angeles, 1971.
11. Sarrafian SK. Functional characteristic of the foot and plantar aponeurosis under tibiotalar loading. Foot Ankle 1987 Aug;8(1):4-18.
12. Root ML, Orien WP, Weed JH, et al: "Static Stance Examination," in *Biomechanical Examination of the Foot,* Vol 1, p. 116, Clinical Biomechanics Corporation, Los Angeles, 1971.
13. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—Part I: ankle, hip, and spine. J Biomech 2002 Apr;35(4):543-548.
14. Perry J, Burnfield JM: Gait Analysis: Normal and Pathological Function, 2nd ed., SLACK Incorporated, Thorofare, NJ, 2010.
15. Leardini A, Benedetti MG, Berti L, Bettinelli D, NativoR, Giannini S. Rear-foot, mid-foot, and fore-foot motion during the stance phase of gait. Gait Posture 2007 Mar;25(3):453-462.
16. Sobel E, Levitz SJ. Reappraisal of the negative impression cast and subtalar joint neutral position. J Am Podiatr Med Assn 1997 Jan;67(1):32-33.
17. Wright DG, Desai SM, Henderson WH. Action of the subtalar joint and ankle joint complex during the stance phase of walking. J Bone Joint Surg 1964 Mar;46A:361-382.
18. Buldt AK, Murley GS, Levinger P, Menz H, Nester J, Landorf KB. Are clinical measures of foot posture and mobility associated with foot kinematics when walking? J Foot Ankle Res 2015 Nov; 8:63.
19. Pierrynowski MR, Smith SB, Mlynarczyk JH: Proficiency of foot care specialists to place the rearfoot at subtalar neutral. JAPMA 1996 May;86(5):217-223.
20. Van Gueluwe B, Kirby KA, Roosen P, Phillips RD. Reliability and accuracy of biomechanical measurements of the lower extremities. JAPMA 2002 Jun;92(6): 317-326.
21. Elveru RA, Rothstein JM, Lamb RL, Riddle DL. Methods for taking subtalar joint measurements. Phys Ther 1988 May;68(5):678-682.
22. Picciano AM, Rowlands MS, Worrell T: Reliability of open and closed kinetic chain subtalar joint neutral positions and navicular drop test. J Orthop Sports Phys 1993 Oct;18(4):553-558.
23. Smith-Oricchio K, Harris BA: Interrater reliability of subtalar neutral, calcaneal inversion and eversion. J Orthop Sports Phys 1990;12(1):10-15.