THE EFFECTS OF ANKLE ORTHOSES AND TAPING ON LOWER EXTREMITY KINEMATICS

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INTRODUCTION

The ankle is the most common injury site in physically active individuals, with lateral ankle sprains being the most frequent injury in sports involving running, jumping, and agility activities. These activities potentially force the ankle to move into excessive inversion (INV) and plantar flexion (PF), which is the most prevalent mechanism of injury for lateral ankle sprains [1-5]. External ankle orthoses and ankle taping are effective strategies to prevent ankle injuries and have been commonly utilized by athletes and physically active individuals [2, 6, 7].

Range of motion (ROM) restriction to prevent excessive INV and PF is a main objective of ankle orthoses and taping. Ankle orthoses restrict INV and PF even after 20-60 minutes of activity [1, 3, 8-11] whereas ankle taping loses its effect as early as 10 minutes of activity [3, 5, 6, 9, 10, 12-15]. The level of ROM restriction provided by ankle taping remains inconsistent throughout the literature; ankle taping provides ROM restrictions in the frontal plane motion more effectively than sagittal plane motions [9, 14, 16-18]. Lace up orthoses are effective in restricting ankle ROM in the frontal and sagittal planes [3, 19], while semi-ridged hinged type of orthoses are effective in restricting frontal plane motion only [7, 11, 20, 21]. However, most of these ankle ROM measurements have been recorded two dimensionally in a non-weight bearing condition, which may not fully represent the functional capabilities of the ankle orthoses or taping in a practical condition [8, 22].

Influence on athletic performance due to ankle ROM restriction is an important consideration. No negative influences of the use of ankle orthoses or taping on various sports specific skills including sprinting, balance, and agility exercises have been reported [6, 9, 10, 19, 23-27]. Vertical jump heights have been reported to decrease up to one inch, however, its practical relevance remains inconclusive [9, 10, 13, 19, 23, 25-29]. While these studies provide critical information considering the use of ankle orthoses and taping for the competitive athletes, individual's biomechanical adaptations to the use of ankle orthoses and taping during a continuous running activity remain unknown.

Therefore, the purpose of the current study was to determine the effect of ankle orthoses and taping on lower extremity kinematics during continuous running activity. We incorporated the assessment of three-dimensional kinematic gait analysis during continuous running activity using two different types of ankle orthoses and ankle taping.

METHODS

Research Design

A randomized repeated measures design was used to investigate the changes in lower extremity kinematics in four different ankle support conditions during a 30-minute exercise bout on a treadmill at a self-selected speed. Ankle support conditions included: semi-ridged hinged ankle orthosis (AA), lace-up ankle orthosis (ASO), adhesive ankle taping (T), and control (C) conditions. The independent variables were ankle support condition and time. The dependent variables were kinematic data.

Participants

Participants included 13 (five male, eight female) physically active adults (Age: 25.07 ± 4.12, Body mass: 70.81 ± 9.59 kg, Height: 1.72 ± 0.08 m); participant characteristics are reported in Table 1. All participants were recruited from the University of Hawai`i at Mānoa and the surrounding Honolulu community. A physically active adult was defined as participating in at least 30 minutes of continuous physical activity three times per week for six weeks prior to the study. The participants completed a medical and injury history questionnaire to screen for cardiovascular disease or other contraindications to study participation. Other exclusionary criteria included lower extremity surgery or injury development within the past six months. Each participant prior to study participation completed consent forms approved by the University of Hawai'i at Mānoa Committee on Human Studies.

Table 1. Participant Characteristics (Mean ± SD)

Participants	Age (years)	Mass (kg)	Height (m)
Female (n=8)	24.38 ± 3.58	64.5 ± 6.77	1.66 ± 0.06
Male (n=5)	24.40 ± 3.36	78.3 ± 4.88	1.78 ± 0.02
Total (N=13)	24.73 ± 4.18	70.74 ± 9.24	1.72 ± 0.08

Instrumentation

Kinematic

A three-dimensional (3D) motion capture system (Vicon MX, Vicon, Inc., Centennial, Colorado, USA), including six Vicon MX13 motion capture cameras (Vicon, Inc., Centennial, Colorado, USA) and Vicon software (Nexus and Polygon, Vicon, Inc., Centennial, Colorado, USA), was used to capture, reduce, and analyze kinematic data. Kinematic data were collected at 240 Hz and smoothed using a fourth-order, low-pass Butterworth filter with a 10 Hz cut off. The Vicon System was calibrated prior to each data collection session according to the manufacturer's instructions with the treadmill raised to a 1% grade [30].

Ankle Supports

Active Ankle T2® (Active Ankle System, Inc., Jeffersonville, IN, USA) was used for a semi-ridged hinged ankle orthosis (AA) condition. Active Ankle T2® is a U-shape hinged ankle brace, which consists of medial and lateral ankle semi-ridged stirrups held in place circumferentially by a single horizontal Velcro® strap. The semi-ridged stirrups are composed of two padded plastic outer shells that are hinged at the malleoli.

Ankle Stabilizing Orthosis® (Medical Specialties, Inc., Charlotte, NC, USA) was used for a lace-up ankle orthosis (ASO) condition. Ankle Stabilizing Orthosis® is a nonhinged ballistic nylon ankle brace, which consists of a lace-up closure, two ballistic nylon straps, and an elastic cuff closure. The straps are designed to encircle the ankle in figure eight patterns from the medial and lateral sides of the ankle brace with self-adhesive Velcro® straps. The elastic cuff closure is a horizontal self-adhesive strap, which wraps around the ankle over the attachment of the figure eight straps.

A closed basket weave (Gibney) ankle taping method was used for an adhesive ankle taping condition. This method involves three stirrups, three circular arch supports, and two heel locks [31]. One and one-half inch Zonas® athletic tape (Johnson & Johnson Service Inc., Langhorne, PA, USA), adherent spray (Cramer Products, Inc., Gardner, KS, USA), two heel and lace pads (Cramer Products, Inc., Gardner, KS, USA), and under wrap (Cramer Products, Inc., Gardner, KS, USA) were used for the ankle tape condition.

Procedures

Data collection involved four randomly ordered testing sessions (ASO, AA, T, C) separated by at least two days. Each session lasted approximately one hour and was scheduled at similar times of day. Participants were asked to maintain similar dietary intakes prior to each testing session and to wear the same shoes for all four testing conditions. The same group of Board of Certification Certified Athletic Trainers (ATC) collected all data in the University of Hawai'i at Mānoa Human Performance Laboratory.

Pre-trial

Anthropometric data including height, weight, true leg length and joint width measurements were collected upon arrival. True leg length was defined as the distance from the anterior superior iliac spine (ASIS) to the ipsilateral medial malleoli [31], which was measured bilaterally with the participant in the supine position using a tape measure. Joint width measurements included bilateral knee and ankle, which were measured using GPM anthropometric spreading calipers (Siber & Hegner, Zurich, Switzerland). Knee flexion-extension axes at medial and lateral joint lines were estimated and used as landmarks for measuring knee width. The most prominent points of medial and lateral malleoli were used as landmarks for measuring ankle width. Ankle width measurements were taken over the ankle support on days for which a support was required (ASO, AA, T). The location of the malleoli over the ankle support for width measurements was approximated using a template created for each participant on the first day of testing. Template development involved the following: (1) The outline of both the left and right shod foot of each participant was traced on a blank sheet of paper in a standing position with the involved foot on a 10-inch box and the ankle and knee each at approximately 90 degrees. (2) A standing ruler was used to measure the height of the most prominent point of the medial and lateral malleoli marked on the skin to the nearest mm. (3) Placement of the standing ruler was traced on the paper in order to standardize measurement and the heights of each malleoli were recorded on the paper. After application of the ankle support, the participant returned to the aforementioned position for the estimation of the malleoli positions. The heights of the malleoli were marked with a pen on the outside of the ankle support and ankle width measurements were obtained based on these landmarks.

Following the anthropometric measurements, all participants completed a five-minute warm-up on a cycle ergometer (Monark 818e, Ergomedics, Vansboro, Sweden) prior to the application of the ankle support. Heart rate during the warm up was maintained at 60% of their heart rate max (HR_{max}), as determined by the equation HR_{max} = 220 – age [28]. Ankle support was applied bilaterally after the completion of the warm-up session. The ASO and AA ankle supports were applied by the participant under the guidance of the ATC based on the manufacturer's instructions. The same ATC applied the ankle tape each time. Following the application of the ankle support, 20 retro-reflective markers were placed on bilateral lower extremity landmarks according to the Vicon system template for plug-in gait [32] using double-sided tape.

Running Trial

Participants performed the 30-minute running trials on the treadmill with a 1% grade, which has been determined to most closely simulate running economy during outdoor running [30]. Prior to the first running trial, participants were instructed to select the running speed to comfortably complete 30 minutes of a continuous run. Once the preferred running speed was determined, it was maintained throughout the 30-minute running trial as well as for the remaining trials under different ankle support conditions.

Kinematic data were collected for five seconds at the beginning and every five minutes over the course of the running trial (at minute 0, 5, 10, 15, 20, 25 and 30). Following the five seconds of running gait recording via Vicon system, the participant was asked to report a RPE for their legs, chest and breathing, and overall feelings of exertion using the Borg's Perceived Exertion and Pain Scales [33]. The Ratings of Perceived Exertion (RPE) was recorded on a data collection sheet along with the average HR of the last 30 seconds of each five-minute segment.

Kinematic Data Reduction Procedure

The running gait captured during the five seconds of recording period was broken down to multiple gait cycles for each leg. The kinematic data during stance phase were utilized for data analysis; twelve (six right, six left) stance phases for each subject in each condition. A stance phase was defined as a period of running gait cycle between heel contact to toe off of the single leg [34]. Due to the absence of force plate kinetic data, initial contact and toe off were identified mathematically and graphically. Initial contact (IC) was identified using the equation, $IC = (Y_{heel} - Y_{ASIS})_{max}$ as reported by Kiss [35], which was the maximum difference between the heel (Y_{heel}) and ASIS (Y_{ASIS}) markers in the Y direction (+Y was the direction of forward movement). Toe off (TO) was identified using the graphical representation (waveform) of the toe markers' vertical (Z plane) acceleration. The largest maximal acceleration was found during the swing phase, with the secondary (local) maximal acceleration found during the stance phase, which was the identifier of TO [36]. The corresponding value of the local maximal acceleration was extracted from the raw data output. The mathematically and graphically determined IC and TO, respectively, were confirmed by visually evaluating the timing of IC and TO on the three-dimensional stick figure model of each participants. The identified IC and TO were considered to be valid when confirmed to be within 5 frames of the visually estimated timing of IC and TO. Sagittal, frontal, and transverse planes kinematic data of ankle and knee joints, and sagittal and frontal planes kinematic data of hip joint at IC and TO, maximal values, and mean values were extracted and included in the analyses.

Statistical Analysis

All statistical procedures were completed using SPSS Version 20.0 (SPSS, Inc., Chicago, IL USA) with an alpha level set at $p<0.05$. Individual repeated measured Analysis of Variance was used to examine the effect of different types of ankle supports (AA, ASO, and T) in reference to the control condition on lower extremity kinematic variables. Independent variables were ankle support type and time (min 0, 5, 10, 15, 20, 25 and 30). The dependent variables included lower extremity kinematics.

RESULTS

Ankle Kinematics

Figures for significant ankle kinematics variables are presented independently in Appendix A. In the frontal plane (Table 2), there was a significant decrease in ankle INV-EV excursion in AA ($p = .008$), ASO ($p = .001$), and T ($p = .001$) at the initial time period; ASO became no longer significant after 25 minutes ($p = .122$), while AA ($p = .006$) and T ($p = .001$) remained significantly decreased at the end of the 30-minute run. Inversion at maximal ($p = .017$) and IC ($p = .008$) significantly decreased in AA at the initial (maximal: $p = .017$, at IC: $p = .008$) and continued to be decreased at final (maximal: $p = .008$, at IC: $p = .010$) time periods. There was a significant decrease in maximal EV velocity in AA ($p = .017$), ASO ($p = .005$), and T ($p = .009$) at the initial time period; ASO became no longer significant after 25 minutes ($p = .196$), while AA and T remained significant at the end of the 30-minute run (AA: $p = .016$, and T: $p = .019$). There were no significant findings for INV/ EV position at TO, maximal EV, and mean EV velocity.

Table 2: Ankle Kinematics in Frontal Plane (Mean ± SD)

Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Ankle INV/EV Excursion (°)							
AA	18.52 ± 5.79*	19.15 ± 5.49*	19.75 ± 5.33*	19.05 ± 5.67*	19.15 ± 5.21*	19.29 ± 5.33*	19.35 ± 5.38*
ASO	16.91 ± 4.80†	17.49 ± 5.62*	16.88 ± 6.09*	18.10 ± 6.06*	17.92 ± 6.12*	18.12 ± 6.06*	20.80 ± 10.3
T	17.05 ± 5.90†	16.33 ± 5.86†	16.67 ± 5.85†	16.68 ± 6.04†	17.74 ± 6.14†	17.92 ± 6.33†	17.92 ± 6.35†
C	25.32 ± 8.84	26.08 ± 8.74	26.67 ± 8.84	26.67 ± 8.84	26.89 ± 9.05	26.86 ± 9.31	26.92 ± 8.91
Ankle INV/ EV Position at IC (°)							
AA	6.43 ± 6.60*	6.12 ± 6.94*	7.57 ± 6.58*	6.13 ± 7.10*	6.38 ± 7.19*	6.70 ± 7.47*	5.92 ± 7.17*
ASO	6.30 ± 9.90	5.53 ± 9.17	6.26 ± 9.29	5.94 ± 9.01	5.79 ± 8.89	6.63 ± 9.73	5.90 ± 10.97
T	7.34 ± 11.96	6.87 ± 11.28	7.28 ± 11.02	7.19 ± 10.86	7.21 ± 11.16	7.12 ± 11.28	8.10 ± 11.34
C	11.26 ± 6.97	11.45 ± 6.30	11.20 ± 6.38	11.10 ± 6.22	10.98 ± 6.54	10.66 ± 6.47	10.37 ± 7.37
Ankle Max INV (°)							
AA	10.32 ± 5.79*	10.50 ± 5.45*	10.73 ± 5.19*	9.75 ± 6.32*	10.32 ± 6.05*	9.93 ± 6.38*	10.11 ± 5.36*
ASO	10.57 ± 8.15	10.27 ± 7.95	10.59 ± 8.59	10.89 ± 8.14	10.51 ± 8.04	11.34 ± 8.29	10.62 ± 8.38
T	10.99 ± 12.51	10.34 ± 11.72	10.87 ± 11.74	10.42 ± 11.31	10.95 ± 11.67	11.22 ± 11.54	11.39 ± 11.79
C	15.38 ± 6.08	15.49 ± 5.57	15.55 ± 5.70	15.38 ± 5.75	15.06 ± 6.10	14.89 ± 5.82	15.85 ± 6.36
Ankle Max EV Velocity (°/s)							
AA	177.94 ±	178.32 ±	202.70 ±	199.19 ±	191.99 ±	193.46 ±	192.46 ±
ASO	168.09 ±	163.56 ±	166.18 ±	167.13 ±	174.88 ±	177.44 ±	217.94 ±
T	178.17 ±	166.35 ±	169.92 ±	170.31 ±	162.68 ±	181.04 ±	196.90 ±
C	267.86 ±	285.62 ±	281.86 ±	284.32 ±	284.90 ±	283.28 ±	284.34 ±

* Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

In the sagittal plane (Table 3), PF at TO and maximal PF were significantly decreased in ASO (initial time: p = .015, final time: p= .001) and T (initial time: p = .012, final time: p = .001) for the duration of the 30 minute run. There was a significant decrease in maximal PF velocity in ASO (p = .000) and T (p = .000) at the initial time period, and both were no longer significant after 25 minutes (ASO: p = .143 and T: p = .057). Maximal dorsiflexion (DF) velocity was significantly decreased in T (p = .047) at the initial time period, but was no longer significant after 25 minutes (p = .084). There were no significant findings for DF-PF excursion, maximal DF, and mean DF velocity.

In the transverse plane (Table 4), internal rotation at IC was significantly decreased in ASO (p = .05) and T (p = .01) at the initial time period and continued to be significant at the end of the 30-minute run (ASO: p = .034, T: p = .044). Internal rotation at TO was significantly decreased in T (p = .01) at the initial time period, but was no longer significant after 25 minutes (p = .100). Ankle maximal internal rotation- external rotation excursion was significantly decreased in ASO and T at the initial time period (ASO: p = .023, T: p = .006) and continued to be significant at the end of the 30-minute run (ASO: p .028, T: p = .018). Maximal internal rotation was significantly decreased in ASO (p = .050) and T (p = .006) at the initial time period; T became no longer significant after 25 minutes (p = .054) and ASO remained significant at the end of the 30-minute run (p = .017). Mean foot progression angle was significantly decreased in AA (p = .01), ASO (p = .05), and T (p = .00) at the initial time period; ASO became no longer significant after 25 minutes, while AA (p = .000) and T (p = .032) remained significant at the end of the 30-minute run. There were no significant findings for maximal external rotation and maximal external rotation velocity.

Table 3: Ankle Kinematics in Sagittal Plane (Mean ± SD)

	Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Ankle Max PF (°)								
	AA	10.89 ± 5.81	10.66 ± 3.92	10.87 ± 3.79	11.31 ± 3.98	10.97 ± 3.95	10.18 ± 4.21	10.40 ± 5.47
	ASO	6.48 ± 3.24*	6.60 ± 4.05*	6.11 ± 5.81*	6.88 ± 5.00*	6.62 ± 4.11*	6.25 ± 4.09*	5.89 ± 3.19*
	T	6.36 ± 6.02†	5.27 ± 5.48*	5.63 ± 5.12*	5.39 ± 5.83*	5.94 ± 5.75*	5.98 ± 5.44*	6.02 ± 5.63*
	C	13.31 ± 9.35	13.72 ± 10.65	13.89 ± 8.87	14.00 ± 9.54	12.53 ± 9.88	12.46 ± 9.42	12.92 ± 8.69
Ankle PF/DF Position at TO (°)								
	AA	10.87 ± 5.79	10.33 ± 4.16	10.85 ± 3.78	11.29 ± 3.96	10.96 ± 3.95	10.18 ± 4.21	10.36 ± 4.54
	ASO	6.49 ± 3.24*	6.57 ± 4.08*	5.71 ± 6.91*	6.73 ± 5.36*	6.51 ± 4.37*	6.17 ± 4.25*	5.89 ± 3.19*
	T	6.05 ± 6.72†	4.94 ± 6.18*	5.00 ± 6.55*	4.95 ± 6.35*	5.67 ± 6.34*	5.74 ± 6.06*	5.60 ± 6.39*
	C	13.29 ± 9.58	13.50 ± 10.90	13.69 ± 8.82	13.72 ± 10.08	12.35 ± 10.22	12.33 ± 9.71	11.97 ± 10.46
Ankle Max PF Velocity (°/s)								
	AA	416.87 ± 92.72	410.70 ± 103.38	416.45 ± 92.71	415.88 ± 91.51	400.79 ± 86.49	410.18 ± 93.35	398.96 ± 89.58
	ASO	373.70 ± 86.02†	379.38 ± 91.30*	372.33 ± 93.29*	376.93 ± 84.25*	370.05 ± 83.36*	367.39 ± 95.27*	371.05 ± 83.16
	T	364.88 ± 93.34†	354.59 ± 84.06†	354.84 ± 83.63†	356.59 ± 80.08†	359.96 ± 80.57†	352.41 ± 86.00†	363.21 ± 93.64
	C	421.19 ± 89.52	416.52 ± 96.66	417.48 ± 81.52	414.73 ± 87.51	411.74 ± 84.30	402.64 ± 89.46	396.88 ± 102.89
Ankle Max DF Velocity (°/s)								
	AA	285.05 ± 38.29	288.46 ± 45.47	291.72 ± 45.25	299.14 ± 51.28	292.39 ± 48.37	296.65 ± 51.68	297.65 ± 48.74
	ASO	275.08 ± 41.73	278.97 ± 37.21	275.85 ± 35.90	278.15 ± 35.19	275.74 ± 40.53	267.94 ± 47.36	272.26 ± 49.40
	T	271.54 ± 49.42*	272.26 ± 49.40*	273.60 ± 51.71*	274.82 ± 47.79*	276.17 ± 51.65*	274.83 ± 60.29*	276.17 ± 51.65
	C	294.36 ± 59.22	297.36 ± 53.72	306.18 ± 57.69	301.74 ± 45.71	303.44 ± 46.24	300.31 ± 52.01	302.53 ± 60.29

* Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

Table 4: Ankle Kinematics in Transverse Plane (Mean ± SD)

	Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Ankle IR/ ER Position at IC (°)								
	AA	3.03 ± 10.80	3.90 ± 9.25	3.36 ± 9.82	4.27 ± 9.12	4.07 ± 9.09	3.62 ± 9.50	4.40 ± 8.06
	ASO	5.48 ± 11.51*	5.76 ± 10.20*	4.04 ± 9.71*	5.81 ± 9.69*	5.51 ± 10.14*	5.80 ± 10.08*	6.03 ± 10.03*
	T	6.28 ± 10.39*	6.83 ± 10.24*	6.72 ± 10.15*	7.22 ± 9.88*	7.54 ± 10.10*	7.35 ± 10.34*	7.24 ± 10.97*
	C	2.97 ± 9.38	2.19 ± 8.73	2.68 ± 9.06	2.52 ± 8.38	2.92 ± 9.07	3.80 ± 8.62	3.09 ± 8.74
Ankle IR/ ER Position at TO (°)								
	AA	2.37 ± 7.47	5.10 ± 6.60	2.48 ± 7.34	1.75 ± 7.31	3.62 ± 6.39	2.37 ± 5.66	4.39 ± 6.65
	ASO	6.17 ± 8.91	6.06 ± 8.27	5.61 ± 6.78	6.00 ± 6.83	6.11 ± 8.04	6.45 ± 7.20	6.95 ± 7.81
	T	8.41 ± 8.56*	8.33 ± 8.56*	8.12 ± 7.57*	9.34 ± 9.24*	8.99 ± 7.82*	9.27 ± 8.77*	7.94 ± 9.94
	C	2.09 ± 6.59	1.35 ± 6.01	2.59 ± 5.64	1.61 ± 7.19	1.73 ± 8.58	2.56 ± 7.93	2.49 ± 6.93
Ankle IR/ ER Excursion (°)								
	AA	21.70 ± 7.45	20.91 ± 6.63	21.14 ± 5.74	20.59 ± 5.84	19.90 ± 5.93	21.34 ± 7.21	20.38 ± 4.98
	ASO	18.20 ± 4.34*	17.61 ± 4.08*	18.73 ± 5.14*	18.03 ± 4.32*	17.46 ± 4.52*	17.75 ± 4.24*	17.36 ± 4.79*
	T	16.35 ± 3.78*	15.41 ± 2.87*	15.47 ± 2.54*	15.39 ± 3.08*	15.92 ± 2.85*	15.28 ± 3.02*	15.53 ± 3.14*
	C	22.53 ± 7.79	22.73 ± 8.26	22.52 ± 8.55	22.60 ± 8.93	21.94 ± 8.48	21.38 ± 8.12	23.08 ± 8.83
Ankle Max IR (°)								
	AA	1.08 ± 8.80	0.34 ± 7.64	1.25 ± 7.68	0.54 ± 7.28	0.01 ± 7.50	1.02 ± 6.93	0.11 ± 6.12
	ASO	2.56 ± 9.80*	2.92 ± 8.88*	1.04 ± 8.37*	2.65 ± 8.32*	2.89 ± 9.19*	2.34 ± 8.49*	2.83 ± 8.61*
	T	3.99 ± 8.93*	4.59 ± 8.71*	4.22 ± 8.84*	4.72 ± 8.64*	4.77 ± 8.55*	4.95 ± 9.40*	3.55 ± 9.11
	C	1.08 ± 6.50	2.27 ± 5.69	2.08 ± 6.04	2.03 ± 6.24	1.37 ± 7.25	0.44 ± 7.06	1.55 ± 7.29
Mean Foot Progress Angle (°)								
	AA	5.35 ± 1.86*	5.29 ± 2.01*	5.36 ± 2.02*	5.80 ± 2.10*	5.63 ± 2.36*	5.58 ± 2.33†	5.43 ± 2.11†
	ASO	5.46 ± 1.66*	5.62 ± 1.85*	5.78 ± 2.09*	5.65 ± 1.83*	5.88 ± 2.01*	5.76 ± 1.93*	6.02 ± 2.03
	T	5.09 ± 1.73†	5.54 ± 2.01*	5.56 ± 2.06*	5.73 ± 2.56*	5.89 ± 2.22*	6.07 ± 2.77*	5.86 ± 2.45*
	C	6.32 ± 1.78	6.59 ± 2.11	6.60 ± 2.03	6.67 ± 1.94	7.15 ± 2.19	6.96 ± 2.64	6.63 ± 2.10

* Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

Knee Kinematics

Figures for significant knee kinematics are presented independently in Appendix A. In the sagittal plane (Table 5), knee flexion- extension excursion was significantly decreased in T at the initial time period (p = .01). Knee maximal flexion velocity was significantly decreased in T (p = .014) at the initial time period but was no longer significant after 25 minutes (p = .267). No significance was found for knee flexion/ extension position at IC and TO, maximal flexion, and mean flexion velocity.

In the transverse plane (Table 6), maximal knee internal rotation was significantly decreased in T (p = .015) at the initial time period but was no longer significant after 25 minutes (p = .120). Maximal knee internal rotation velocity was significantly decreased in T at the initial time period (p = .009) and continued to be significant at the end of the 30-minute run (p = .021). There were no significant findings for knee internal rotation/ external rotation position at IC and TO, internal rotation-external rotation excursion, and mean internal rotation/ external rotation velocity. Also, there were no significant findings in the frontal plane variables for the knee.

Table 5: Knee Kinematics in Sagittal Plane (Mean ± SD)

	Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Knee Flex/ Ext Excursion (°)								
	AA	30.71 ± 4.52	31.99 ± 4.57	31.96 ± 4.75	32.51 ± 4.03	31.64 ± 3.57	32.53 ± 4.39	31.85 ± 5.23
	ASO	29.36 ± 4.81	29.94 ± 5.22	30.16 ± 4.77	31.27 ± 5.02	31.44 ± 5.14	31.59 ± 4.85	31.60 ± 5.33
	T	28.52 ± 4.45*	28.78 ± 4.05*	29.71 ± 5.20	30.13 ± 4.61	30.10 ± 4.42	30.06 ± 4.70	31.59 ± 3.78
	C	30.97 ± 5.39	30.59 ± 4.24	30.51 ± 5.09	31.64 ± 3.57	31.89 ± 4.82	31.78 ± 5.48	32.10 ± 4.78
Knee Max Flex Velocity (°/s)								
	AA	399.78 ± 61.62	422.55 ± 81.25	426.73 ± 100.5	431.08 ± 82.87	412.54 ± 69.29	434.32 ± 92.19	432.65 ± 93.96
	ASO	390.16 ± 56.33	405.55 ± 78.96	395.27 ± 71.91	400.48 ± 66.44	414.27 ± 82.04	417.28 ± 83.00	411.86 ± 84.35
	T	370.86 ± 47.75*	387.60 ± 77.06*	389.84 ± 76.59*	393.65 ± 84.96*	394.46 ± 77.35*	407.18 ± 90.81*	411.77 ± 97.28
	C	412.53 ± 86.54	422.23 ± 78.11	420.32 ± 79.24	438.11 ± 88.17	436.30 ± 96.22	441.81 ± 97.28	428.93 ± 95.45

* Significance at $p < 0.05$ compared to controls

Table 6: Knee Kinematics in Transverse Plane (Mean ± SD)

	Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Knee Max IR (°)								
	AA	17.82 ± 7.44	16.86 ± 6.16	17.21 ± 6.57	17.39 ± 5.98	17.35 ± 5.91	18.73 ± 6.41	17.30 ± 6.39
	ASO	14.77 ± 6.50	15.19 ± 6.24	15.66 ± 6.45	15.78 ± 6.53	15.93 ± 6.43	16.23 ± 6.50	16.69 ± 6.92
	T	11.79 ± 4.91*	12.15 ± 4.56*	12.63 ± 4.78*	12.52 ± 4.65*	12.85 ± 4.63*	13.03 ± 4.82*	14.13 ± 5.26
	C	16.31 ± 5.96	16.57 ± 6.04	16.58 ± 6.57	17.15 ± 5.95	17.15 ± 6.05	17.42 ± 6.25	17.67 ± 6.71
Knee Max IR Velocity (°/s)								
	AA	248.58 ± 97.890	253.24 ± 105.06	254.65 ± 101.45	266.36 ± 101.10	273.09 ± 118.12	291.63 ± 115.53	292.14 ± 137.25
	ASO	216.34 ± 58.95	236.14 ± 69.75	267.95 ± 83.41	251.24 ± 85.24	262.26 ± 90.22	273.50 ± 79.26	274.33 ± 97.61
	T	190.27 ± 60.87*	214.58 ± 84.06*	225.79 ± 92.74*	227.69 ± 81.67*	233.48 ± 96.05*	255.34 ± 120.08*	247.55 ± 107.08*
	C	264.90 ± 105.85	275.68 ± 86.200	299.79 ± 90.830	305.81 ± 111.86	307.86 ± 105.21	315.31 ± 114.36	324.33 ± 138.41

* Significance at $p < 0.05$ compared to controls

Hip Kinematics

Figures for significant hip kinematics variables are presented independently in Appendix A. There were no significant findings for sagittal plane variables of the hip. In the frontal plane (Table 7), hip adduction at IC was significantly increased in AA, ASO, and T at the initial time period (AA: p = .026, ASO: p = .005, T: p = .015,); T became no longer significant after 25 minutes (p = .075), while AA and ASO remained significant at the end of the 30-minute run (AA: p = .007, ASO: p = .023). Hip abduction- adduction excursion was significantly decreased in ASO at the initial time period (p = .008) and continued to be significant at the end of the 30-minute run (p = .033). Mean hip abduction velocity was significantly decreased in ASO at the initial time period (p = .002) and continued to be significant at the end of the 30-minute run (p = .005). There were no significant findings for abduction/ adduction at TO, maximal abduction, maximal adduction, and maximal adduction velocity.

Table 7: Hip Kinematics in Frontal Plane (Mean ± SD)

	Condition	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
Hip ABD/ADD Position at IC (°)								
	AA	5.08 ± 2.73*	5.42 ± 3.00*	6.33 ± 2.46*	6.36 ± 2.30*	6.46 ± 2.38*	6.34 ± 2.26*	6.59 ± 2.24*
	ASO	5.43 ± 3.42*	5.51 ± 3.99*	5.65 ± 3.05*	5.63 ± 3.51*	5.95 ± 3.78*	5.95 ± 4.20*	5.94 ± 3.57*
	T	5.16 ± 3.57*	6.04 ± 3.52*	6.23 ± 3.45*	6.03 ± 3.35*	6.03 ± 3.25*	6.46 ± 2.99*	5.90 ± 3.51
	C	3.79 ± 3.64	4.39 ± 3.57	4.24 ± 3.44	4.47 ± 3.58	4.69 ± 3.54	4.98 ± 4.16	4.56 ± 3.84
Hip Excursion (IC to Max ABD) (°)								
	AA	7.86 ± 2.99	9.02 ± 3.00	9.00 ± 3.08	9.12 ± 3.15	9.15 ± 3.35	9.12 ± 2.77	9.59 ± 3.03
	ASO	8.80 ± 2.75*	8.82 ± 3.56*	9.00 ± 3.47*	8.94 ± 3.53*	8.65 ± 3.71*	8.95 ± 3.24*	9.02 ± 3.81*
	T	8.05 ± 3.34	8.49 ± 2.92	9.34 ± 3.36	8.57 ± 3.56	8.26 ± 3.71	8.86 ± 3.08	8.42 ± 3.57
	C	7.46 ± 3.85	8.25 ± 3.99	8.04 ± 3.78	8.16 ± 4.20	8.14 ± 3.78	8.17 ± 4.71	8.02 ± 4.00
Hip Mean ABD Velocity (°/s)								
	AA	23.44 ± 10.71	27.85 ± 10.71	27.34 ± 10.18	28.11 ± 9.67	27.74 ± 10.65	27.34 ± 9.17	28.73 ± 10.18
	ASO	26.90 ± 9.470*	27.31 ± 12.73*	27.58 ± 10.87*	27.34 ± 10.59*	27.55 ± 11.07*	28.47 ± 14.01*	28.59 ± 10.72*
	T	26.25 ± 10.39	26.15 ± 9.01	28.44 ± 11.08	26.94 ± 10.36	25.91 ± 10.88	26.93 ± 9.59	26.08 ± 11.17
	C	21.79 ± 12.22	25.05 ± 11.45	23.27 ± 13.53	25.28 ± 11.10	25.96 ± 10.57	24.34 ± 13.38	24.66 ± 11.39

* Significance at $p < 0.05$ compared to control

Discussion

The current study, to our knowledge, is the first to report three-dimensional kinematics during a continuous 30-minute run for three different ankle support conditions compared to control. Kinematic changes in the T and ASO conditions were found consistently after 25 minutes of exercise, indicating that degradation of the supports occurred around this time period. Previously reported duration of the ROM restriction effect varied most likely due to the differences in methodology for obtaining measurements. Most commonly, measurements were taken by hand-held goniometer in an open-kinetic chain position [10, 26]. Static open chain measurements have indicated 40-50% loss of ankle ROM restriction in tape conditions after 10 minutes of exercise [3, 5, 6, 9, 10, 12-15, 37]. Dynamic high velocity, closed chain measurements indicated less tape degradation in inversion compared to low velocity, open chain inversion [8, 22]. Overall, previous studies have reported that the tape degradation occurs sometimes between 15 minutes to 20 minutes of running exercises [7, 27]. Our result suggested that the T and ASO were effective in restricting ROM up to 25-minute of exercise, while AA was effective in restricting ROM through out the 30-minute of exercise.

Decreased ankle INV-EV excursion in AA, ASO, and T compared to C occurred throughout the 30-minute run. Maximal INV and INV angle at IC were significantly decreased only in the AA condition and remained decreased throughout the 30-minute run. These restrictions seen with AA, while not in ASO or T, are possibly due to the rigidity of the medial-lateral hinge design. Ricard et al. [18] reported that most ankle injuries occurred between 30 to 50 milliseconds after IC. The ability of AA to prevent ankle injuries may be augmented by decreased INV at IC. Our result suggests that all ankle supports, AA, ASO, and T, have the ability to decrease frontal plane motion, which could potentially minimize the risk of injuries.

Sagittal plane restrictions were found only in the T and ASO conditions, while no sagittal plane restrictions were found in AA due to the lack of supportive structures covering the anterior and posterior portions of the ankle. In the current study, there was a significant decrease in maximal PF and PF at TO in ASO and T. Significant decreases in PF velocity in ASO and T were also seen, indicating a decreased rate of PF during the propulsion stage of running gait. Dorsiflexion kinematics were affected only in T, with a significant decrease in maximal DF velocity. A significant decrease in knee flexion velocity was also found only in T. During the stance phase of running, maximal DF velocity occurs as the body weight is being loaded onto the limb while the tibia advances over the foot [38]. Based on the coupling mechanism of DF and knee flexion during the loading phase of running gait, decreased maximal DF and knee flexion velocity found in the current study suggest a decreased rate of loading and tibial advancement, which may influence performance that involves dynamic sagittal ankle movement.

Reduction of DF velocity potentially decreases the stretch of the Achilles tendon complex, causing a decrease in the eccentric loading of the gastroc-soleus complex. If decreased eccentric loading is present, the power output of the plantar flexors may decrease as well. Rapid force production is vital to vertical jump performance, because the muscle-tendon relationship is highly dependent on the speed and intensity of the movement[39]. Previous research has reported that ankle supports do not influence the magnitude of anterior-posterior ground reaction force, however, the time in which the force is applied is significantly increased suggesting the ankle and foot attenuate forces by extending the amount of time in which they act [40, 41]. Decreased PF ROM and velocity during propulsion found in the current study, in conjunction with the previous finding of increased force application time could potentially cause a shift in the timing of anterior-posterior forces during push-off. This mechanism could be associated with the decreased vertical jump height in taped conditions [39]. More research is needed to evaluate the potential changes in timing of push-off, and its influence of ankle moments with T or ASO.

Effect of ankle supports and tape on the transverse plane has not been previously reported; however, restriction of transverse motion at the ankle could potentially play a role in preventing lateral ankle sprains. Hintermann [42] found after releasing the calcaneofibular ligament in cadavers, there was a 61% increase in internal rotation of the ankle, showing that an intact ligament plays a role in the restriction of ankle internal rotation. In addition, Inman found the anterior talofibular ligament effectively restricts talar movement including the motion in the transverse plane [43]. Maximal internal rotation was significantly decreased in ASO and T due to the multi-directional pull of the Velcro straps or tape, which was not seen in the AA. Additional support provided by ASO and T in the transverse plane suggests that ASO and T are more effective in providing multi-planar support to the ankle.

Mean foot progression angle during stance was significantly decreased in all conditions. Foot progression angle is measured between the axis of the foot and the line of progression, and is often referred to as toe-in or toe-out gait [44]. A significant decrease was found in all conditions indicating a more forward foot position in relation to the path of progression. Huang et al. [44] reported decreased foot progress angle in individuals with chronic ankle instability (CAI), and concluded that this forward foot position was a compensatory mechanism to increase the foot stability. The decrease in foot progression angle caused by AA, ASO, and T may further stabilize the individuals with CAI who are already utilizing this compensatory gait pattern.

Significant decreases in maximal knee internal rotation and internal rotation velocity were found in the current study. Previous research has shown that a decrease in ROM in one segment can cause changes at another segment [45, 46]. Based upon biomechanical system configurations, internal rotation of the knee can more accurately be described as internal rotation of the tibia on the femur. In relation to the tibia, the talus is a key structure linking the tibia to the distal structures [22]. Under weight-bearing conditions, talorcrural, subtalar, and transverse tarsal joints transfer torque between the leg and foot [22, 46]. Theoretically, tibial rotation produces a rotation at the ankle. Bellchamber et al. [45] describes this coupling of internal rotation and external rotation of the tibia resulting in pronation and supination of the ankle complex respectively as negative power flow. Bellchamber et al. [45] did report brief periods of a positive power flow during running, indicating motion at the distal segment has the ability to influence the rotation at the proximal segment. Since ankle taping restricts pronation [47], the tape can potentially restrict internal rotation of tibia via restriction of pronation [45].

Significant differences found at the hip may be due to rigidity at the ankle causing modulation to occur. We found a significant increase in hip adduction angle at IC in AA and ASO conditions throughout the 30-minute run, compared to controls. Hip adduction angle at IC was also increased in T condition until 25-minute. Novacheck [38] reported that an increase in hip adduction at IC acts as a “shock absorbing mechanism”. Using frontal plane absorption mechanism at the hip to compensate for the restricted sagittal plane motion at the ankle may explain our finding of increase in hip adduction angle at IC. The coinciding events of T degradation and hip adduction angle at IC returning to the control level at 25 minutes further supports this mechanism.

Limitations of the current study were associated with a use of treadmill protocol. Although 1 % grade was utilized to mimic over ground running, previous study reported that treadmill running might not be an accurate representation of over ground running [48]. Incorporating kinetic analyses and a thoracic segment to the kinematic model would provide further insight into the effects ankle supports have on the dynamic running biomechanics of the lower extremity. Finally, our participants represent healthy, physically active population with no previous ankle injuries; therefore, the results of this study may not be applicable to the individuals with CAI.

Clinical Application

Since athletes commonly use ankle orthoses to prevent inversion ankle sprains, it is important to understand which method would be most effective. According to the NATA Position Statement [49], prophylactic ankle supports are more effective in preventing recurrent ankle sprains compared to first ankle sprain. Athletes with history of previous ankle sprains utilizing orthoses or tape had approximately 70% fewer ankle injuries than those who chose not to use ankle supports [50]. Chronic Ankle Instability occurs when an athlete has a history of recurrent ankle sprains and is described as a “giving way” sensation during exercise [51]. Tanen et al. [51] reported that 30% of athletes will develop CAI after the first ankle sprain.

The current study found AA to significantly restrict inversion, compared to controls, while allowing for normal kinematics in the sagittal and transverse planes. Athletes with a multi-directional instability may benefit more from an ASO or T, which effectively restrict multi-planar motion at the ankle joint. Tape has a greater effect on the proximal joints, primarily the knee, though, previous research suggests the application of tape or orthoses does not increase the prevalence of knee injuries [52-54]. Since increased internal rotation of the tibia is often linked to increased risk of overuse knee injuries [55, 56], our finding of decreased internal rotation of the tibia caused by T support the previous findings of no increased risk of knee injury due to tape application. For the athlete returning from an ankle sprain, it may be beneficial to use a combination of AA and T initially if multi-directional instability is of main concern. The combination of AA, for restriction of maximal inversion and inversion at IC, and taping, for the restriction of multi-planar motion, is recommended post-injury for the maximal effect of ankle support.

REVIEW OF LITERATURE

The purpose of this study was to determine the effect of two ankle orthoses and ankle taping, when compared to controlled conditions, on lower extremity kinematics during continuous running activity. In the review of literature, the sections presented are: Anatomy and Prevalence of Injury at the Ankle, Range of Motion Restriction Methods, Performance, and Methodology.

Anatomy and Prevalence of Injury at the Ankle

When evaluating the effect of external ankle supports on ankle injuries, it is important to understand the prevalence of ankle injuries using different ankle supports. Previous research has remained consistent on the role external ankle supports play on injury prevention, however, differentiating between which ankle support method offers the best injury prevention is needed for recommendation.

Anatomy of the Ankle

Wilkerson [22] extensively reviewed previous research to understand the underlying mechanisms by which ankle supports attempt to provide beneficial effects. Wilkerson focused on the assessment of inward displacement of the hindfoot within the frontal plane. Other researchers have reported the importance of pathologic rotary displacement of the talus in the transverse plane with the frequency of subtalar joint ligament lesions and the effect of ankle supports on deceleration of INV velocity and neuromuscular response. The lateral subtalar-sling taping may limit strain of the ATF ligament, restrain anterolateral rotary subluxation of the talus in presence of ligament laxity, and protect the ligaments from excessive loading. This may enhance hindfoot-to-forefoot force transfer during the push-off phase of the gait cycle. Taping offers a means to address the complex interrelated biomechanical factors that are responsible for subtalar joint injury and rotary instability of the talocrural joint.

Hintermann[42] thoroughly examined the biomechanics of the unstable ankle joint complex and applied this information in the clinic when dealing with patients with both acute and chronic stability conditions. The ankles of 50 cadavers were used to test the length, ROM, and force production allowed at the ligaments around the ankle. Once released, the calcaneofibular ligament increased 61% in talocalcaneal adduction. Injury to the calcaneofibular ligament may result in greater symptomatic subtalar instability. The rotation of the talus with respect to the tibia depends significantly on the integrity of the deltoid ligament.

Stiehl and Inman [43] studied the anatomy and kinematic relationship of the ankle and subtalar joints in a published textbook entitled "Inman's Joints of the Ankle." Inman modeled the ankle joint complex using various hinged wooden models and studied the forces placed upon the ankle joint and ligamentous structures using cadaveric specimens with soft tissue removed. In chapter seven, the author describes biomechanical functions of the joints at the ankle and offers an understanding of function of the network of ligaments at the ankle. They describe the subtalar joint as a mitered hinge as a directional torque transmitter. Pronation is defined as external rotation of the foot relative to the tibia combined with hindfoot EV and outward rotation of the foot on its own longitudinal axis. Supination is defined as internal rotation of the foot on the tibia combined with hindfoot INV and inward rotation of the foot about its longitudinal axis. When the foot pronates, the tibia is internally rotated. Alternately, when the foot supinates the tibia is externally rotated. Inman found that the anterior talofibular and calcaneofibular ligaments were effective in restricting movement of the talus in the transverse plane.

Hamill, Knutzen, Bates, and Kirkpatrick[41] evaluated ground reaction force data of two ankle stabilizing techniques, closed Gibney taping procedure and boot type ankle stabilizer compared to controls. Eight healthy female athletes performed 10 trials in each condition before and after an exercise bout. No significant differences in any of the force or impulse variables were found across conditions. However, significant differences were found in three variables at the relative timing of events in the footfall ($p > .05$). No significant differences were found between the pre- and postexercise conditions. The variability in the measured parameters of the control condition was higher than the ankle support conditions.

Nawoczenski, Saltzman, and Cook [46] investigated the effect of foot structure on three-dimensional kinematic behavior of the leg and rear foot during running. Based on radiographic measurements, 10 recreational runners were assigned to a high rear-foot group and 10 recreational runners were assigned to a high rear-foot group. Kinematic data were collected during a treadmill running bout. Cardan angle systems of three order rotations were defined by coupling the leg and rear-foot segments. Calcaneal EV and INV was favored for the low rear-foot group ($p < .05$) and tibial medial and lateral rotation for the high-rear foot group ($p < .05$). The differences between groups found the coupling ration to be proportional to the amount of calcaneal EV and INV transferred or coupled to tibial axial rotation.

Bellchamber and van den Bogert[45] studied the cause and effect relationship between tibial internal rotation and pronation of the foot during walking and running. Kinematic and kinetic data were collected on 20 subjects who performed 10 running and 10 walking trials across a force plate. The authors used a least-squares algorithm to determine attitude matrices for each segment in each frame to calculate the angular velocity vector of the tibia. In walking, all subjects showed a clear power flow from foot to tibia during most of the stance phase; therefore, the foot segment motion was based upon the tibial segment motion. During running, power flow was also mainly proximal to distal, but did have brief periods of opposite power flow. Eversion of the foot and internal rotation of the tibia was also shown to have a nearly linear correlation. Power flow for normal subjects during running remained small for the first 10-20% of stance. A brief period of distal to proximal motion control from the foot to tibia was seen between 40 to 60% of stance with female subjects tending to have larger oscillations.

Huang, Lin, Kuo, and Liao[44] evaluated foot pressure and center of pressure (COP) patterns in individuals with ankle instability during running and lateral shuffling. Eleven subjects with ankle instability (AI) and 11 normal subjects performed running and lateral shuffling tasks. Subjects completed the Cumberland Ankle Instability Tool (CAIT) questionnaire to screen for AI. Inclusion criteria of the AI group included the following basis: (1) having at least one ankle sprain that involved swelling and pain; (2) experiencing an ankle “giving way” during exercise; (3) having at least one ankle sprain in the past year; and (4) having a CAIT score below 24. Subjects ran across a pressure plate mounted in a wooden walkway at a comfortable speed, but lateral shuffling was performed as fast as possible. For running, foot progression angle for the AI group was significantly lower than the normal group ($p < .001$). During stance phase, the AIF group had significantly greater ($p<0.05$) contact area percentage in the midfoot but smaller contact area percentage ($p = .004$) in the forefoot compared to normal. The main findings of this study were, in running, subjects with unstable ankles had a lower foot progression angle and higher M1 and M3 peak pressures. A "mobile foot type," which allows more EV during stance, has been one factor in the occurrence of ankle sprains. A lower foot progression angle, or decreased toe out, affects the foot INV-EV moment and foot kinematics and ground reaction force during walking gait. A lower foot progression angle suggests that subjects run with a less inverted foot during the early and late stance phase.

Noehren, Davis, and Hamill[57] compared prospectively lower extremity kinematics and kinetics between a group of female runners who developed iliotibial band syndrome (ITBS) compared to healthy controls. The authors hypothesized that the runners who developed ITBS will exhibit greater peak hip adduction, knee internal rotation, rearfoot eversion and no difference in knee flexion at IC. A group of healthy female recreational runners completed the gait analysis and were tracked for injury for the next two years. Eighteen runners developed ITBS and were compared to a group of age and mileage matched controls without a history of knee or hip pain. Peak knee internal rotation angle was significantly higher in the ITBS group ($p = .01$). Tibial internal rotation was lower in the ITBS group by 2.2 degrees but was not significant. While knee internal rotation was greater in the ITBS group, tibial internal rotation was less than the controls. The authors concluded that the increased knee external rotation seen in the ITBS group may be related to muscle imbalances at the hip.

Prevalence of Ankle Injuries

Garrick, JG[2] reviewed the frequency of injury, mechanism of injury, and epidemiology of ankle sprains. Basketball and football were compared as the most prevalent sports involving prophylactic ankle taping with ankle sprains being the most common injury to these athletes. The typical mechanism of injury is INV, PF, and internal rotation, usually injured in "dynamic" fashion. The shortness of the medial malleolus and natural tendency for the ankle to invert rather than evert, usually results in lateral ankle sprains. Garrick concluded that, despite the use of prophylactic ankle support, ankle sprains remain a major threat to participants in nearly all sports.

Kaminski et al.[49] presented recommendations for athletic trainers and other allied health care professionals in the National Athletic Trainers' Association Position Statement: Conservative Management and Prevention of Ankle Sprains in Athletes. Recommendations were made on the areas of ankle sprain diagnosis, treatment and rehabilitation, return-to-play considerations, prevention, and special considerations. A literature review was presented on current research on physical examination: history, observation, palpation, special tests, and multiple imaging techniques. Taping and bracing were recommended for use prophylactically in an effort to prevent a first-time ankle sprain or to prevent recurrent ankle sprains. Regardless of the type of support, prevention of injury was suggested to be more effective in people with a history of ankle injuries.

Dizon and Reyes [50] evaluated the effectiveness of external ankle supports in preventing inversion ankle sprains and identification of the ankle support with the highest evidance for injury prevention. Two reviewers assessed the quality of studies found in a search for literature using the Joanna Briggs Institute Appraisal tool. A total of seven trials were used in this study. The participants consisted of adolescent and adult elite or recreational players with no history of ankle injuries or lower extremity injuries. Ankle sprain occurrence was significantly reduced by 69% in ankle bracing and by 71% in ankle taping among previously injured athletes. The authors concluded that no specific type of ankle support was better at reducing injury over the other.

Garrick and Requa [52] examined the role of external ankle supports in the prevention of ankle sprains. Two thousand five hundred and sixty-two college intramural basketball players were evaluated during two successive intramural season to evaluate the frequency of ankle and knee sprains in relation to ankle support use. The use of prophylactic ankle taping ($p < .05$) and high-top shoes ($p < .05$) significantly decreased the frequency of ankle sprains. There was a significant decrease of ankle sprains using these prophylactic strategies in those individuals who had a previous ankle sprain ($p < .05$). There was no increase in the occurrence of knee sprains from using high-top shoes or prophylactic ankle taping.

Tanen et al. [51] determined the prevalence of chronic ankle instability (CAI) among high school and Division I collegiate athletes. Chronic ankle instability is defined as the history of recurrent ankle sprains and having a sensation of “giving way” during exercise. Exclusionary criteria included history of ankle fracture or surgery, neurological disorders, or failure to completely answer the questionnaires. Data were collected using a general demographic questionnaire, Cumberland Ankle Instability Tool (CAIT), and Ankle Instability Instrument (AII). Frequencies were used to determine the overall prevalence and percentage of unilateral or bilateral CAI. A nonparametric chi-squared test of independence was used to associate CAI and gender, level of participation, severity of initial ankle sprain, and limb dominance. Of the 512 participants, 23.4% had CAI and half of these having bilateral CAI. The authors found that high school athletes were more likely to have CAI than collegiate athletes ($p < .001$). Women had a higher prevalence of CAI than men in both high school ($p = .01$) and collegiate ($p = .01$) athletes.

Surve, Schwellnus, Noakes, and Lomabard [54] evaluated the effect of a semi-rigid (Sport-Stirrup) on the incidence of ankle sprains in soccer players during one season. Players were divided into two groups: previous ankle sprains (N= 258) and no previous history (N= 246). At the start of the season, each player was randomly allocated to either the semi-rigid orthosis or the un-braced control group. The incidence of ankle sprains was significantly reduced in the orthosis group with previous sprains compared to the control group with previous sprains. This study concluded that a semi-rigid orthosis was effective in reducing the incidence of recurrent ankle sprains in soccer players with previous history of ankle sprains.

Glick, Gordon, and Nishimoto [53] examined the role of ankle supports in the prevention and treatment of ankle injuries. Over six seasons of intercollegiate football, from 1969 to 1974, 396 ankles in 198 football players had inversion stress x-rays taken prior to practice. The degree of talar tilt was measured and the players were divided into two groups: significant talar tilt (over 5 degrees) and insignificant talar tilt (under 5 degrees). The effectiveness of tape and a cloth wrap were used to assess support of talar tilt. The tape restricted the ankle for no more than 20 minutes of exercise. The cloth ankle wrap did not restriction ankle motion. The study suggested that the advantage of using tape is caused by the stimulating effect on the peroneus brevis muscle in a dynamic action. The tape did not increase the prevalence of knee injuries.

In regards to the prevention of ankle sprains, external ankle supports are effective, specifically in those with recurrent ankle sprains[49, 50, 52, 54]. The use of orthoses seem to be most effective due to its design[54], by the user tightening the straps to continue the restriction throughout the exercise. Tape has been seen to degrade after 15 to 20 minutes of running exercise[53], causing the clinician to re-tape the athlete multiple times if exercise lasts longer than 20 minutes, in order to continue restriction throughout the exercise.

Range of Motion Restriction

A component of lower extremity kinematics is the measurement of joint angles throughout the gait cycle. Ankle orthoses and taping methods have been seen to restrict to joint range of motion (ROM) before activity, but taping methods have seen decreases in these restrictions after activity[4, 5, 7, 9, 12, 16, 53]. The methods of obtaining ROM measurements have varied throughout the literature.

Static and Open-Chain Measurement Methods

Cordova, Ingersoll, and Palmieri [40] provided a comprehensive review of the literature for the role of external ankle supports on joint kinematics, kinetics, sensorimotor function, and performance. Most studies investigating the effects of ankle supports on joint kinematics have involved passive ROM evaluation using an isokinetic dynamometer or goniometric device after some type of exercise. Lace-up braces provide greater overall EV ROM restriction than tape. Dorsiflexion ROM was restricted 38.3% more with taping than with a lace-up brace. No significant difference was found between tape and lace-up on overall PF ROM restriction. Since ankle supports reduce joint angular displacement and angular velocity, the authors concluded that these supports attenuate the external forces that cause angular motion. There has been conflicting research on vertical jump performance with ankle supports. The different results among studies are most likely due to the various testing procedures employed. A variety of starting positions were used, with some allowing the dominant foot to step forward first, while others required a step approach. Most researchers placed the subject in a crouched position before the vertical jump. The mechanism for reduction in vertical jump performance is due to the design of the lace-up brace and adhesive tape. These supports produce restrictions of plantar flexion ROM, which can diminish vertical jump performance. Although some studies have shown ankle supports to negatively effect vertical jump performance, most of the literature in this area has demonstrated no damaging effects of such supports.

Rarick, Bigley, Karst, and Malina [5] compared the support of the ankle joint by conventional methods of taping before and after exercise. Five healthy males (21-28 years) volunteered for this study. Four different ankle taping conditions were used: basketweave, basketweave with stirrups, basketweave with heel locks, and basketweave with stirrups and heel locks. Ankle ROM was measured before and after exercise with the volunteer supine using a foot aligner, mounted tensiometer, and ROM indicator. The exercise consisted of a 10-minute period of activity (running, jumping, pivoting, quick starts, and quick stops). Pearson correlations and means for each of the two trials before and after exercise in each support condition were calculated. An analysis of variance was also used to determine interactions between the individuals, support conditions, and exercise condition. After 10 minutes of exercise, the support provided by each strapping technique was substantially less than before the exercise ($p < .05$). The support provided by the tape was decreased by 40% after 10 minutes of exercise.

Myburgh, Vaughn, and Isaacs[4] measured the ability of two types of tape and two different ankle guards in restricting ROM before and after participation in a one-hour squash match. Twelve squash players (age 18-22) participated in two consecutive squash matches, wearing an ankle guard on one side and having the ankle taped on the other side. Both of the ankle guards were elastic in nature (Ace guard and Futuro guard). The two types of tape used were a zinc oxide, closed basketweave tape and an elastic tape. A different ankle guard and tape were applied for the second match. An electronic goniometer measured PF, DF, PF with INV, PF with EV, INV, and EV under the following conditions: unsupported before exercise, supported before exercise, after 10 minutes of exercise, after one hour of exercise and unsupported after exercise. Neither of the ankle guards significantly ($p < 0.05$) restricted ROM before, during or after activity. Both the zinc oxide tape and elastic tape restricted ROM before exercise and until 10 minutes of exercise (except the elastic tape in DF). Both types of tape loosened and provided no significant restriction after one hour of exercise. The ability of both taping techniques to restrict ROM decreased from 20-40% before exercise to 10-20% after one hour of exercise, in all motions except DF ($p = .01$). The authors report that the ankle guards were not effective in restricting ROM and that although the zinc oxide tape displayed the greatest ability to restrict ROM, both the zinc oxide and elastic tape loosened and were not effective in supporting the ankle after one hour of exercise.

Fumich, Ellison, Guerin, and Grace[16] measured the effects of taping on combined foot and ankle motion before and after a 2.5 to 3 hour football practice. Sixteen male college-aged football players with no history of lateral ankle sprain participated in this study.

The ankle ROM was collected before the Zinc Oxide, closed basketweave taping method was applied, before exercise, and after exercise. An Inman ankle machine recorded PF, DF, INV in neutral, EV in neutral, PF with INV, and PF with EV. Mean values in degrees in each motion for taped, non-taped, and taped post-exercise. A single paired t-test was used to determined the minimum degree of restriction that can be expected with tape after a 2.5 to 3 hour practice. The average restrictions were: PF (4.18 deg), DF (1.0 deg), EV (3.31 deg), INV (6.38 deg), PF with INV(5.81 deg) and PF with EV (1.13 deg) with a 90% confidence interval. EV, INV, and PF with INV decreased less than 50% of initial restriction caused by taping ($p < .05$). PF, DF and PF with EV loosened greater than 50% of initial restriction due to taping ($p < .05$).

Kimura, Nawoczenski, Epler, and Owen[11] evaluated subtalar ankle INV with and without AirStirrup application using high speed cinematographic techniques and INV platform at 35°. Eighteen subjects (19-35 years) with no history of ankle injury participated in this study. The same ankle was tested for each of the two trials taken, AirStirrups applied to both ankles in one trial and neither in the other trial. Points were marked on the posterior knee, Achilles tendon, and distal calcaneous that were digitized and smoothed to calculate the maximum angular displacement of inversion at the subtalar joint. Significant increases in INV were found in the ankle not braced compared to the AirStirrup ($p<0.001$).

Gross, Bradshaw, Ventry, and Weller[20] compared the effectiveness of ankle taping and a semi-rigid orthosis in limiting ankle ROM before and after exercise. Eleven students (two male and nine female, 18-22 yrs) from the University of North Carolina at Chapel Hill, with no history of ankle injury, volunteered for this study. Subjects were separated into two groups, taping and orthosis (Air Stirrup), and passive ankle ROM (INV, EV, and total) was tested with a Cybex II Isokinetic Dynamometer. Measurements were taken before and after the exercise bout consisting of 10 minutes of running a figure of eight course followed by 20 toe raises. Statistical interaction was found between treatments and testing sessions for total motion ($F=15.26$, $p<0.01$), INV ($F=8.62$, $p<0.01$), and EV ($F= 19.35$, $p<0.01$). This study indicated that both taping and orthoses significantly restrict ankle INV-EV following application. The results show that the orthosis provided greater restrictions in motion in INV and EV than the application of tape ($p < .01$). This suggests that a semirigid orthosis may be more effective at preventing lateral ankle sprains than tape.

Greene and Hillman,[7] investigated INV and EV ROM, as well as the effect of the different ankle support systems on vertical jumps performance, before, during and after a three-hour volleyball practice. Seven female volleyball players (age 18-21) were divided into two groups: adhesive ankle tape (Group 1) and Ankle Ligament Protector (ALP) orthosis (Group 2). Baseline ROM was measured passively using an analog ankle stability test and measurements included INV, EV and total ROM. All three measurements were taken before exercise without support, before exercise with support, after 20 minutes of exercise, after 60 minutes of exercise and after the three-hour practice session. On the final day of testing, all participants completed vertical jump performance testing without support, with tape support, and with the ALP ankle brace. There was significant degradation of the tape in all three ROM measures within the first 20 minutes ($P < 0.01$) and a continued reduction in restriction of INV and total ROM after 60 minutes and three hours of exercise ($P < 0.01$). Taping did not demonstrate significant loosening in EV after 60 minutes or three hours of exercise ($P > 0.01$). There was significant loosening in EV and total ROM after the three-hour practice ($P > 0.01$). The ability to restrict ROM decreased from 41% to 15% for the taping condition and 42% to 37% for the ankle brace condition during the three-hour practice. The authors suggest that ankle supports may be more effective in reducing INV ankle sprains. Although vertical jump heights were reduced under both conditions, the results were not statistically significant ($P > 0.01$), demonstrating that neither condition significantly affects performance.

Greene, and Wight[3] compared the support effectiveness of three ankle orthoses before, during, and after a 90-minute softball practice while assessing base running ability. Twenty-four ankles with no history of ankle pathology were divided into three groups (n=8) and randomly assigned to wear one of the ankle supports: Air-Stirrup, Ankle Ligament Protector (ALP) and Swede-O orthoses. Passive INV-EV ROM was measured on an ankle stability test instrument during five testing sessions: pre-support, pre-exercise, 20 minutes during exercise, 40 minutes during exercise, and post-exercise. A Significant interaction was found in support effectiveness among the three orthoses ($p<0.01$). The support post-exercise by the Swede-O was reduced by 35% compared to pre-exercise ($p < 0.01$). The support reductions for the Air-Stirrup and the ALP were 12% and 8%, respectively. The ALP and Swede-O orthoses had no significant effect on the ability to run bases, but the Air-Stirrup resulted in significantly slower ($p< 0.05$) base running times.

Gross et al.[12] measured the ROM of 16 participants (32 ankles) before and after exercise while wearing either a DonJoy ALP or while having the ankle taped using the subtalar sling (SS) method. The support system was applied bilaterally. Participants were measured for passive EV and INV before application of the support system, after application of the support system, and after exercise. Passive ROM was measured using a Biodex dynamometer. For the exercise portion of the trial, participants ran on a 5 x 10-m figure-of-eight course at a self-selected speed for 10 minutes. The participants then completed 20 unilateral toe raises (weight-bearing PF efforts) on a 15.42-cm step. The ROM of one leg on one participant exceeded the mechanical ability of the Biodex hardware and was subsequently omitted from statistical analysis, leaving 31 ankles available for analysis. Inversion and EV ROM was significantly ($p < 0.05$) restricted for both support systems after the initial application when compared to pre application measurements. Both support systems loosened and provided significantly less but equivalent ROM after exercise. While both support systems also provided significant INV restriction after application, the SS system provided more restriction than the ALP ($p < .05$). The support systems provided significant restriction of INV ROM after exercise when compared to pre application measurements ($p < .05$); however the SS support significantly decreased from its pre exercise measurement ($p < .05$), while the ALP did not. The INV measurements between the support systems after exercise were not statistically different. Subjective information gathered from the participants resulted in the ALP being reported the most comfortable support while the SS was reported to be more supportive and more cosmetically acceptable.

Paris, Vardaxis, and Kokkaliaris[9] studied the effects of exercise on ROM while wearing an ankle brace or having the ankle taped. Range of motion was tested at different points in time during exercise: unsupported, pre-activity (0 minutes) and after 15, 30, 45 and 60 minutes of exercise. Thirty participants performed four randomly ordered trials wearing ankle tape, a SubTalar Support-brace, a Swede-O brace, or unsupported. Passive INV, EV, PF and DF were measured using a modified Inman Ankle machine during each of the six measurement times. Ten minutes of exercise were performed on a treadmill between each of the measurements. All ankle support systems provided significant restriction in INV and EV ROM at 0 min ($p < .001$), as well as significant restriction of PF ($p < .001$) and DF ($p <$

.001), when compared to the unsupported condition. Statistical analysis revealed that PF ROM for the tape condition increased significantly ($p <0.05$) after 15 minutes and continued to decrease at 30, 45 and 60 minutes. ROM also increased significantly for taped condition in EV after 15 minutes ($p < .001$), INV after 15 min ($p < .001$) and DF increased after 45 minutes ($p = .007$). There was a significant increase in ROM for the SubTalar Support-brace in PF after 15 minutes ($p < .001$), INV after 15 minutes ($p < .001$) and INV between 15 and 30 minutes ($p < .001$). There was no significant difference in EV or DF ROM after activity for the SubTalar Support-brace. There was a significant increase in ROM for the Swede-O brace in INV after 15 minutes ($p < .001$), PF after 30 minutes ($p = .004$) and EV after 60 minutes ($p < .001$). Overall, the Swede-O brace provided the greatest amount of EV restriction (81%) and retained INV and PF support longer than the SubTalar Support-brace or tape.

Wiley and Nigg[58] tested the effect of a Malleoloc ankle orthosis on active and passive ROM reduction of the ankle joint and on a figure of eight running and jumping performance. Twelve, eight male and four female, adults (24.2 +/- 3.8 years) with a history of previous ankle sprains were selected for this study. Active and passive DF, PF, EV, and INV were measured with an Inman ankle machine before and after exercise. The exercise included a five-minute warm-up on a stationary bike, five minutes running on a course, cycling for 10 minutes, and then jogging on a treadmill at a self-selected speed for 15 minutes. The application of the Malleoloc ankle orthosis and standardized shoe occurred before the first ROM measurement. Variables measured were: jumping height, running time, DF, PF, EV, INV, 20 degrees DF, neutral, 20 degrees PF, and 40 degrees PF. The orthosis was shown to restrict ankle INV throughout the exercise as well as other orthoses ($p < .01$).

The restriction to PF and DF was minimal ($p < .05$). The authors concluded that orthoses in general could affect performance negatively.

Metcalfe, Schlabach, Looney and Renehan[13] compared the effectiveness of moleskin tape, linen tape, and a lace-up brace on motor performance and ankle ROM. Ten college females (26.5 ±3.69 years) with no recent ankle injury history volunteered to participate in this study. The effects of three ankle applications (taping (T), tape and moleskin (TwMSR), brace (B)) on performance limitations, as measured by vertical jump and Southeast Missouri (SEMO) agility test, on ankle ROM before, during, and after a 20-minute exercise bout. The passive ROM (DF, PF, INV, and EV) was measured using a hand-held goniometer before application, after 10 minutes, and at the end of the 20-minute exercise protocol. Vertical jump performances for all three ankle conditions were significantly shorter ($p \leq .0001$) as compared with the control condition. Compared to controls, there was a significant reduction in PF during exercise when wearing the TwMSR and B applications ($p \leq .0001$). The T and TwMSR applications significantly restricted EV when compared with controls ($p \leq .0001$). All three were significantly effective in restricting DF and INV compared to controls. The authors concluded that the TwMSR condition significantly restricted all four ROM tested, where T and B conditions limited only three of four ROMs tested. All three conditions significantly reduced performance compared to controls.

Purcell et al. [17] evaluated the effectiveness of self-adherent tape and white cloth tape on maintaining ankle ROM restriction before and after activity. Twenty Division 1 university students (19.8 ± 1.7 years, 11 females) with no history of lower extremity injury participated in this study. An ankle electrogoniometer measured the active INV-EV excursion and PF-DF excursion between self-adherent tape, white tape, and no tape. Measurements were taken at a baseline before tape application, pre activity, and post activity in each condition. The activity consisted of a five minute warm-up then 20 minutes of various drills: lateral shuffles, forward/ backward running, agility ladder, figure of eight, 90 degree cuts with lateral shuffle, wall jumps, forward jogging while jumping over cones, and zigzags. Self-adherent tape was shown to restrict INV-EV ROM to a greater degree than either white tape or no tape conditions ($p < .05$). For DF-PF ROM, both white tape and self-adherent tape restricted ROM before and after exercise ($p < .05$).

Miller et al. [14] examined the effectiveness of taping and bracing on restricting ankle motion before and after exercise, in individuals with and without ankle instability, as well as a group of ankle sprain copers (COP). Twenty-four (18 female, 20.6 ± 1.6 years) healthy individuals with no previous ankle history participated for the study. Ankle laxity was measured using an instrumented ankle arthrometer, performing anterior (ANT) displacement, followed by INV-EV rotation. Subjects completed three sessions of testing: taped condition (closed basketweave with heel locks and figure eights), a braced condition (ASO EVO ankle brace), and no tape or brace (No-EPS) condition. For each session, subjects performed a five minute warm up on a stationary bike, then began 20 repetitions of functional exercise protocol (FEP) consisting of sprints, side shuffles, backpedal, lateral hops, and box jumps. In both taped and braced conditions, laxity increased significantly from pre to post exercise ($p<0.01$) with the exception of a trend ($p=0.065$) observed in the braced condition in the COP group. Significant decrease ($p<0.001$) in INV and EV rotation in the tape and brace conditions compared to the No-EPS condition, both pre and post exercise. Tape was significantly more restrictive than the brace following exercise with INV ($p=0.004$) and EV (p=0.009). Tape proved to provide more restriction in INV and EV post-exercise, when compared to the brace.

Dynamic and Closed-Chain Measurement Methods

Martin and Harter[8] compared the INV ROM of 10 participants (age = 23.4 ± 2.5 years) during treadmill walking and running in four conditions (control, closed basketweave ankle taping, Swede-O Universal ankle brace and Aircast Sport-Stirrup ankle brace). Active INV ROM was assessed for each participant before and after physical activity using a handheld goniometer and 2-D analysis of videotaped kinematic data. Each participant was videotaped pre- and post-exercise while walking (4 mph) and running (9 mph) on a treadmill tilted 8.5° laterally. The physical activity intervention included repeated bouts of an obstacle course for a total of 20 minutes. The obstacle course was designed to include forward sprinting, lateral movements, vertical jumping and backwards running. The maximum INV angle means were statistically different among all four conditions during both walking ($p = .001$) and running ($p = .001$) on the treadmill. The Sport-Stirrup allowed the least amount of INV both before and after physical activity during treadmill walking (7.6 ± 3.1° and 10.7 ± 4.0°, respectively). The Sport-Stirrup and Swede-O ankle supports provided the same amount of INV restriction during post-exercise treadmill running (11.9 ± 2.2° and 11.9 ± 3.5°, respectively). These two supports provided the greatest amount of post-exercise INV restriction during treadmill running. All ankle support conditions decreased ROM in open chain measurements compared to the control ($p < .05$). Overall, the Swede-O Universal ankle support provided the greatest amount of open chain INV restriction pre- and post-exercise (7.6 ± 2.5° and 11.7 ± 3.0°, respectively). All support systems were ranked based on their ability to restrict INV pre- and post-exercise. Ankle taping was ranked as the least effective method (2.83) while the Swede-O Universal and Sport-Stirrup ankle supports tied for the most effective methods (1.58).

Pederson et al. [15] compared the effects of spatting alone, taping alone, spatting and taping, and control conditions on the amount and rate of INV of the ankle before and after exercise. Fifteen male rugby players (22.9 ± 3.3 years) with no history of lower-leg injury within six months volunteered. A platform was used to produce a sudden INV of the right ankle to 35°, positioned in view of a shuttered video camera. Ankle INV ROM and rate of INV were tested under the four conditions before and after a 30-minute period of rugby drills. Reflective markers were placed on the subject's gastrocnemius, Achilles tendon, and top and bottom of the right shoe to detect INV-EV of the calcaneus while the subject was on the INV drop platform. After exercise, a significant increase in the amount of INV for the taped, taped and spatted, and spatted treatments were found ($p < 0.001$). The amount of INV during the untaped condition changed from 32.9° before exercise to 33.5° after exercise ($p = .00$). The ankle taping condition significantly reduced INV ROM by 11.5° (35%) before and 6.6° (20%) after exercise ($p < .01$). A 30-minute exercise bout resulted in an increase in the magnitude and rate of INV. All three taping methods were effective in reducing the magnitude and rate of INV compared to controls. The combination of spatting and taping was the most effective in reducing the amount and rate of INV before and after exercise.

Ricard, Sherwood, Schulthies, and Knight[18] tested the effect of taping over prewrap on restricting dynamic, weightbearing INV. Thirty subjects (17 males, 13 females, 24.9 ± 4.2 years) with no lower extremity injury, volunteered for this study. An INV platform was used to produce a sudden INV of the right ankle to 37°, while an electronic goniometer placed on the subject's heel was used to measure ankle INV, before and after activity. Surface electromyography (EMG) was used to record the level of activity of peroneus longus and tibialis anterior to monitor pre-activation. The subject's ankle was taped using a closed basketweave with heel locks and figure eights before the 10 trials on the INV platform were performed. Subjects then performed an exercise bout of a 10-minute treadmill run (9.66 kph), running figure eights, shuttle runs, and bilateral toe raises. Total INV was significantly less, by approximately 10°, during the two tape conditions than during the control condition ($p <.001$). Time to maximum INV was greater for the tape conditions than control both before and after exercise, despite the lesser distance ($p < .001$). Average INV velocity was 38% and 40% less during tape conditions than control before exercise and 29% and 31% after exercise ($F(2,58)= 89.42$, $P<.001$). There was no significant difference in total INV, average INV velocity, maximum INV velocity, or time to maximum INV between taping to the skin and taping over prewrap before and after exercise. Tape decreases the INV velocity and increases the time to achieve maximum INV, possibly allowing the neuromuscular system additional time to respond.

Kitaoka et al.[59] assessed the effects of custom-made polyproplene orthoses, ankle-foot orthosis (AFO), rigid hind-foot orthosis (HFO-R) and articulated hindfoot orthosis (HFO-A) on gait. Twenty normal, asymptomatic individuals (10 female, 27-65 years) volunteered for this study. Three-dimensional kinematics and kinetics were collected at a self-selected walking velocity in four conditions (five trials each): shoe only, and shod with AFO, HFO-R, and HFO-A. Both the AFO and HFO-R significantly ($p <0.05$) reduced maximal hindfoot PF and total hindfoot sagittal motion, compared with the unbraced shot and HFO-A conditions ($P< .05$). The AFO had shown less hindfoot DF than the HFO-A.

All three orthoses significantly ($p < 0.05$) reduced the maximal hindfoot INV and total coronal motion compared with the unbraced shod. The AFO and HFO-R were associated with significant ($p < 0.05$) decrements in cadence with respect to the HFO-A and unbraced shod. This study concluded that alteration in gait was affected by the orthosis design due to the rigidity across the joint restricting the ROM at that joint, potentially compromising typical gait factors.

DiStefano, Padua, Brown, and Guskiewicz[1] evaluated immediate and long term effects of ankle bracing on lower extremity kinematics and ground reaction forces during a jump landing. Forty-two, healthy recreational volleyball and basketball players (18-22 years, 20 female) participated in this study. Each subject participated in two sessions of five jump down trials with an ASO brace and without the brace. An electromagnetic motion analysis system was used to analyze and reduce kinematic data and smoothed with a Butterworth filter at 14.5 Hz cutoff. Kinetic data were measured with a nonconductive force plate, which the subjects jumped down to from a box height. In the brace condition, ankle PF at initial ground contact (brace- 38° ± 15°, $p = .024$), maximum DF (brace- 21° ± 7°, no brace- 22° ± 6°, $p = .04$), DF ROM (brace- 56° ± 14°, no brace- 59° ± 16°, $p = .001$), and knee flexion ROM (brace- 79° ± 16°, no brace- 82° ± 16°, $p = .036$) all significantly decreased, where knee flexion at initial ground contact increased (brace- 12° ± 9°, no brace- 9° ± 9°, $p = .0001$). The ASO brace used in this study appeared to restrict ankle motion without increasing knee extension or vertical GRFs while not changing kinematics or kinetics over time.

Paulson and Braun [60] examined the effects of prophylactic ankle taping on lower extremity kinematics and running economy during treadmill running. Twelve recreational runners completed two 20-minute running sessions (taped and untapped) at a self-selected speed. Lower extremity kinematics at IC and TO, stride frequency, and stride length were calculated. Running economy was calculated as oxygen uptake per unit body mass per kilometer as running speeds varied. Hip angle at TO significantly decreased in tape ($p = .01$) by 3.82 degrees compared to controls. The ROM tended to decrease over the 20-minute run ($p = .08$). Tape did not significantly affect the physiological measures with metabolic cost of treadmill running or the other kinematic variables.

Ubell, Boylan, Ashton-Miller, and Wojtys [21] compared the success rate of three ankle braces in resisting a standardized dynamic forced-INV stimulus. Fourteen healthy men (mean age 25.1 years) completed the forced dynamic ankle INV (24 degrees) by landing on one foot onto a hard, level force plate in three different brace (Aircast, Bledsoe, and Swede-O) conditions. The average no-brace success rate was 24% and all three braces increased the success rate, average 44%. However, only two semirigid braces proved to be significantly better than the unbraced state; the Bledsoe ($p = .006$) and Aircast ($p = .006$) braces were more effective than the Swede-O in preventing INV. This continues along with previous research stating semirigid braces are more effective than lace-up braces at resisting INV.

Nishikawa et al.[47] examined the effects on the kinematic behavior of the ankle complex of the semi-rigid Air-Stirrup brace, lace-up cloth RocketSoc brace, ankle taping, and the ankle without bracing. Rearfoot pronation-supination angle and the shift of COP during walking were measured. Four women and eight men without history of ankle injury or other lower extremity injury, walked across a 7 m walkway at a self-selected speed. The right foot of each subject received one of the four conditions during the session. Maximum pronation angle was significantly increased in lace-up brace ($p < .05$) and tape ($p < .05$)

compared to unbraced. Touchdown supination angle was significantly decreased in lace-up brace ($p < .01$) and tape ($p < .01$) compared to unbraced. Ground contact was displaced laterally using a lace-up brace and taping method. Lateral displacement of COP at touchdown was significantly increased by 13.06% in lace-up brace ($p < .05$) compared to semi-rigid brace. The author concluded that a less stable foot at TO resulting from increased pronation with the use of ankle supports may also lead to impaired performance. In taping, the medial side of the ankle joint is simultaneously stabilized from the use of a stirrup; this could potentially prevent large pronation velocity, which was observed using the lace-up cloth brace.

Stoffel et al.[61] measured the changes in knee and ankle kinetics and kinematics during dynamic athletic activities undertaken with and without ankle taping. Twenty-two healthy males pariticipated in running and sidestepping tasks to determine ankle and knee joint motion and loading in planned and unplanned conditions with or without ankle tape. At the knee, peak internal rotation moments ($p < .001$) and peak varus moments ($p < .05$) were significantly reduced during all running and sidestepping trials in taped conditions. Internal rotation impulse ($p < .001$) was reduced for sidestepping tasks. Range of motion at the ankle in all three planes ($p < .05$) was significantly reduced by tape. Peak INV ($p < .001$) was significantly reduced for running trials only. Ankle taping provided protective benefits to the knee via reduced internal rotation moments and varus impulses during both planned and unplanned activities.

Sinclair et al.[48] extensively compared three-dimensional kinematics of the lower extremities during over ground and treadmill running. Twelve subjects ran at 4.0 m/s in both treadmill and overground running conditions. Kinematic parameters during stance were collected at 250 Hz using an eight-camera motion analysis system. Hip flexion at IC and ankle excursion to peak angle were significantly reduced during treadmill running by 12 degrees (p = .001) and 6.6 degrees (p = .010), respectively. Peak ankle EV was significantly increased by 6.3 degrees (p = .006) in treadmill running. The authors concluded that mechanics of treadmill running could not be assumed to be equivalent to over ground running.

Novacheck [38] evaluated sprinting biomechanics compared to walking and running in 27 healthy children aged five to 18 years. They were testing in normal walking then asked to run as fast as they could during the running/ sprinting section. A Vicon system with a standard retro-reflective marker set and four in-line AMTI force plates were used to obtain and process the data. An important finding in conjunction to our findings, Novacheck reported that decreased knee flexion velocity is more important in shock absorption. In sprinting, it is important for generating energy for forward propulsion. Novacheck illustrated in figures, the timing of lower extremity kinematics in a percentage of the gait cycle in walking, running, and sprinting. During running gait, Novacheck describes the coupling mechanism of ankle DF and knee flexion during loading as the tibia advances over the foot.

The level of ROM restriction due to ankle taping has remained variable throughout the literature. Restrictions in the frontal plane motions are preserved throughout activity more effectively than sagittal plane motions[3, 9]. Sagittal plane ROM in lace-up orthoses has shown no differences compared to tape; however more rigid orthoses have restricted sagittal motion to a greater degree after exercise[7, 11, 21]. Previous research has been inconclusive on the effects of ankle orthoses and taping on ankle motion during functional activity.

Performance

When considering an external ankle support, clinicians must evaluate the potential changes to performance, depending on the activity and the amount of restriction provided by the ankle support. Many sports require successful performance in activities such as, sprinting, balance, agility, vertical jump, and running.

Callaghan[27] reviewed the literature on taping and presented evidence available to taping helps supports ankle. The most common mechanism of injury for ankle sprain is excessive INV with slight PF and some internal rotation. The effects of orthoses on performance on tests of vertical jump, sprint, and agility were taken into account from multiple articles on the topic. The literature review reported that the majority of authors [7, 19, 25, 26, 58] found no effect to performance from a orthoses condition[27]. Two articles[24, 29] did report detrimental effects to vertical jump with a Swede-O-universal orthosis[27]. Callaghan concluded that the majority of studies have shown that braces restrict ankle motion less than taping without affecting performance.

Burks, Bean, Marcus, and Barker[29] evaluated the effects of different ankle support devices on athletic performance in broad jump, vertical leap, 10-yard shuttle run, and 40-yard sprint. Thirty college athletes performed with both ankles supported by taping, Swede-O brace, Kallassy brace, or unbraced. Compared to unbraced conditions, ankle taping resulted in significant decreased ($p<0.05$) performance in vertical jump (4%), shuttle run (1.6%), and sprint (3.5%). The use of the Swede-O braced decreased ($p < .05$) performance in vertical jump (4.6%), broad jump (3.6%), and time of sprint (3.2%). The Kallassy brace decreased ($p < .05$) vertical jump (3.4%) when compared to unbraced. For the shuttle run, times were significantly slower ($p<0.05$) with taping than the Kallassy brace. The Swede-O braced caused broad jump distances to significantly decrease ($p<0.05$) compared to the Kallassy brace.

Paris[19] studied the effects of taping and bracing on performance in 18 elite soccer players (age = 17.6 ± 1.7 years). Each participant completed four performance tasks with five different conditions (control, nonelastic adhesive tape, MacDavid ankle brace, New Cross Ankle Brace and Swede-O ankle brace). The performance tasks included a 50-yard sprint, The Nelson test of static and dynamic balance, the SEMO agility test and the Sargent Chalk Jump Test. The order of the performance tasks and conditions were randomized. Statistical analysis with repeated measures found no significant differences between any of the conditions and tasks, except for the New Cross brace during the Sargent Chalk Jump Test. The New Cross brace showed a significant decrease ($p<0.05$) of 5.4% in vertical jump height compared to the untaped condition (22.22 ± 2.34 in vs. 23.50 ± 29 in, respectively). There was also a significant decrease ($p<0.05$) in vertical jump height among the other ankle support conditions; however the differences were not significant.

Beriau, Cox, and Manning[6] assessed the effects of four different ankle braces on agility performance (Aircast Sports Stirrup, Aircast Training brace, Swede-O brace, and DonJoy ALP). Eighty-five high school athletes were evaluated with four conditions (2 control trials and 2 different braces) while running an agility course. The course consisted of forward running, backward running, lateral shuffling and directional changes. The braces were randomly assigned and two control trials were done in order to account for a learning effect. Participants completed a questionnaire after performing the tasks and subjectively evaluated each brace for support, comfort and restriction of speed and quickness. Participants were also asked which brace they would prefer if they were required to wear one. There was a significant difference (p < .0001) between the two control trials, which led the authors to suggest that a learning effect occurred. The Aircast Training brace allowed the participants to perform the agility course significantly quicker than the DonJoy ALP (22.3s vs. 22.7s, p < .05). There was no statistical difference in speed when the other braces were compared. The Swede-O brace was preferred among participants (42%) and was reported to have excellent support, comfort and low restriction of speed and quickness. The DonJoy ALP was the least preferred brace (9%). The authors point out that although participants had statistically slower times in the ALP brace, it is an insignificant amount when taken into account during an actual athletic event. They report that braces have little effect on practical performance but that a participant's comfort in the brace may be an influencing factor.

Bocchinfuso, Sitler, and Kimura[26] compared the effects of two semirigid prophylactic ankle stabilizers (Active Ankle Training Brace and Aircast SportStirrup) on performance to vertical jump, 80-foot sprint, shuttle run, and four-point run. Fifteen freshman high school boys or girls basketball players, with no ankle injury history in the past year, participated in this study. Each subject performed the four events, three times for each condition (Active Ankle, Aircast, or unbraced). The results of this study indicated that neither brace had a significant effect on vertical jump, 80 ft sprint, shuttle run, or four-point run performance.

Gross et al. [23] compared the effects of the Ankle Ligament Protector (ALP) and Aircast Sport Stirrup (AS) on three functional performance tasks: the 40-m sprint run, the figure-of-eight run, and the standing vertical jump. Sixteen (8 females, ages 18-34) individuals with no history of ankle injury six months prior to testing participated in the study. During the test, each subject performed a 320-m warm-up run, and then performed each task twice with a three-minute rest period between each trial. Analysis of variance indicated that the two orthoses did not differ significantly in their effects on any of the functional performance tasks, and there were no significant differences between braced and unbraced data for any of the performance tasks.

Macpherson, Sitler, Kimura, and Horodyski[25] assessed performance of 25 high school football players (16 ± .99 years) while wearing two different types of ankle braces (the Aircast Sport Stirrup and the DonJoy RocketSoc) and with a control condition. All participants were measured on performance in a 40-yard sprint, 20-yard shuttle run and a vertical jump test. The order of the conditions and performance tasks were randomized over a four-day period. Statistical analysis revealed that neither of the braces had a significant effect on the performance of the sprint test, shuttle run or vertical jump test.

Quackenbush, Barker, Stone, and Behm[10] examined the effects of two adhesive ankle taping methods on strength, power, and ROM in female athletes. Eleven female college basketball athletes (20.6 ± 1.4 years) participated in the study. The two adhesive taping methods consisted of a Gibney closed basketweave with heel locks and a Gibney closed basketweave with heel locks and figure eights. Active ankle ROM was measured with a universal goniometer in PF and DF before and after activity. The activity began with a 10 minute run on a treadmill at 9.6 km/hr, then each of the following exercises performed twice: vertical jump, countermovement jump, drop jump, squat jump, and concentric only squat jump. The active ROM, pre and post, stayed restricted in both taping methods. There were no significant differences on vertical jump, contact time, or maximal voluntary contraction force.

MacKean, Bell, and Burnham[24] assessed the functional performance of 11 female basketball players (age 17-25) with four ankle support conditions. The ankle support conditions used included Active Ankle Training Brace, Aircast Air-Stirrup Ankle Brace, Swede-O-Universal Ankle Brace, and a closed basketweave taping technique. The participants performed the following performance tasks: vertical jump, jump shot, sprint drill (time) and 15-min steady state run at 6 mph. Metabolic measurements of oxygen consumption (VO_2), respiratory exchange ratio (RER), and heart rate (HR), were collected and averaged during the last 5 minutes of the test for the calculate energy expenditure. No significant difference was found between the ankle braces in the vertical jump test; the ankle tape condition was significantly lower than the no support conditions (248 cm vs. 252 cm, respectively; $p < .05$). Jump shot accuracy was significantly improved in the taped condition over the Swede-O ankle brace condition (7.2 shots vs. 5.5 shots, respectively; $p < .05$). The ankle tape condition demonstrated the lowest VO_2 and the least energy expenditure (2.4 $L^{-1}/kg^{-1}/min^{-1}$ and 12.1 kcal/min, respectively; $p < .05$). The Aircast ankle brace had the highest VO_2 and the highest energy expenditure (2.7 $L^{-1}/kg^{-1}/min^{-1}$ and 13.5 kcal/min, respectively; $p < .05$). Overall, functional performance was affected by ankle support type. The authors suggest that the increased energy expenditure may be related to joint restriction caused by the ankle support.

Earp et al.[39] determined if the muscle-tendon structure is associated with the rate of force development (RFD) throughout static squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ) in 25 strength- and power- trained men. Ultrasonography was used to measure pennation (PEN) and fascicle length (FL) of the Vastus lateralis (VL) and gastrocnemius (GAS) and thickness and length of the Achilles tendon (AT). Subjects performed each exercise to calculate RFD over five distinct time intervals. During CMJ, early RFD could be predicted between 0 and 10 milliseconds by both GAS-FL and AT-length ($p > .05$). Between 10 and 30 milliseconds GAS-FL was a significant predictor of CMJ-RFD ($p > .05$). During DJ, initial RFD could be significantly predicted by GAS-FL ($p = .014$), VL-PEN ($p = .030$), and GAS-PEN ($p = .030$). The GAS-FL has an intensity-dependent relationship with RFD during vertical jumping. Both strength and plyometric training has been shown to increase FL, only heavy resistance training has been shown to increase PEN. When a high eccentric load or multiple jumps are required for sport, heavy strength training should be used to allow for early force production during jumping.

Verbrugge [37] determined the effectiveness of Air-Stirrup ankle bracing and adhesive ankle taping on performance. Twenty-six male athletes performed an agility run, 40-yard sprint, and vertical jump in three conditions, adhesive tape, Air-Stirrup brace and control. No significant effect on was seen in measures of agility, sprinting speed or vertical jump was observed in both taping and bracing. Although not significant, the brace and tape reduced jump heights by 2.5% and 2.9%, respectively. The difference in perceived comfort ratings reported by subjects with respect to support system shows that subjects were more comfortable using the brace over a standard ankle taping procedure. The most convincing evidence for choosing the brace over the tape is the perceived comfort ratings; more subjects rated the brace as comfortable or very comfortable.

Performance seems to be unchanged after the application of external ankle supports; however, MacKean et al[24] and Burks et al[29] found effects to vertical jump in a tape and orthosis condition. Many activities associated with lateral ankle sprains incorporate periods of continuous running. Ankle ROM restriction due to orthoses or taping may affect the lower extremity in ways that would alter normal movement patterns during running.

Methodology

The various supporting literature for the methodology used in this study has been described. As our study will have the subject running on a treadmill, it is important to consider the proper gradient where reflect the most accurate energy cost. Another important aspect to understand in our study is the subject's perceived exertion during the treadmill run to correspond with the oxygen consumption (VO_2). Since this study lacks kinetic data, initial contact and heel contact must be defined along with a successful stance phase.

Jones and Doust[30] determined the treadmill gradient that most accurately reflects the energy cost of outdoor running. Nine trained male runners ran for six minutes at six different velocities (2.92, 3.33, 3.75, 4.17, 4.58, and 5.0 m/s) with six-minute recovery between runs. This was repeated six times, five times on a treadmill set at different grades (0%, 0%, 1%, 2%, 3%) and once outdoors along a level road. Oxygen consumption was collected during the final two minutes of each run. This study demonstrates the quality of metabolic cost of treadmill and outdoor running with the use of a 1% treadmill grade over a duration of ~5 minutes and at velocities between 2.92 and 5.0 m/s. ($p < 0.05$).

Borg[33] introduces, through his book *Borg's Perceived Exertion and Pain Scales*, the field of perceived exertion with the application of Rate of Perceived Exertion (RPE) and Category Ratio (CR10) scaling methods. The participant reports an RPE value for their legs, chest and breathing, and overall feelings of exertion according to the pain scales ranging from 6-20, which is to follow the general heart rate of a healthy adult by multiplying the number by 10.

ACSM's Guidelines for Exercise Testing and Prescription[28] summaries recommended procedures for exercise testing and exercise prescription in healthy and diseased individuals. During the metabolic testing done for this study, we determined the heart rate (HR) needed during the warm up period, which was 60% of the of their heart rate max (HR_{max}), as determined by the equation from ACSM (HR_{max}= 220 – age).

Whittle [34] introduces the procedure of gait analysis through his book, *An Introduction to Gait Analysis*. This book describes the biomechanics of both normal and pathological gait. Whittle defines one successful stance phase as initial contact to toe off of the single leg.

Prentice and Arnheim[31] emphasizes through their text, *Arnheim's Principles of Athletic Training: A Competency-Based Approach*, the prevention and management of athletic injuries and remains the only text to cover all aspects of the profession of athletic training. Inside the text, the authors describe the technique of ankle taping in a closed basket weave (Gibney) ankle taping method, including three stirrups, three circular arch supports, and two heel locks. True leg length is also defined inside the text as the distance from the anterior superior iliac spine (ASIS) to the ipsilateal medial malleoli.

In *Vicon Plug-In Gait Product Guide - Foundation Notes*[32] , the various system templates for plug-in gait were demonstrated on where reflective markers were to be placed on the subject's body. The system used in our study was the standard lower body plug-in gait. In this system, the markers were placed: at the Left Anterior Superior Iliac (LASI), Right Anterior Superior Iliac (RASI), Left Posterior Superior Iliac (LPSI), Right Posterior

Superior Iliac (RPSI), Right Thigh (RTHI), Right Knee (RKNE), Right Tibia (RTIB), Right Ankle (RANK), Right Heel (RHEE), Right Toe (RTOE), Left Thigh (LTHI), Left Knee (LKNE), Left Tibia (LTIB), Left Ankle (LANK), Left Heel (LHEE), and Left Toe (LTOE).

Kiss [35] compared kinematics-based and ground reaction force (GRF)-based event detection methods. Initial contact (IC) and toe off (TO) were determined from Zeni et al[62] as the position of foot markers in direction X (+X was direction of forward movement) versus the position of ASIS in direction X was a sinusoidal curve that oscillated about the origin. HS would be represented as the peak of the curve and TO as the valley. The equations used were: $HS_{kin}= (X_{heel} – X_{ASIS})_{max}$ and $TO_{kin}= (X_{heel} – X_{ASIS})_{min}$. These techniques were shown effective when compared with GRF based event detection, along with confirming its accuracy when used on a treadmill surface.

De Witt[36] presented a new method for the detection of TO during walking and running on a treadmill while verifying using ground reaction force data. During treadmill locomotion, especially running, overground methods may not be as accurate. Ten subjects walked and ran on a treadmill while a motion-capture system extracted positional data from the heel and toe markers. The methods of Zeni et al[62] were used to determine the time of HS and TO for each stride for both the coordinate and velocity methods. For the TO method, acceleration and jerk of the toe marker along the vertical axis were found at the local maximum in vertical toe marker acceleration during the period between previous HS and the next local maximum vertical heel marker position. The time of TO was determined using the vertical component of the toe marker, which found the greatest accuracy for the event detection. The methods described can be used to determine IC and TO during treadmill locomotion using only kinematic data.

Zeni, Richards, and Higginson[62] introduced and discussed two computational methods of determining treadmill and overground gait events from kinematic data. The objective was to evaluate the ability of two algorithms to predict the gait events compared to predicting events using vertical ground reaction force (GRF). Seven healthy young adults, seven adults with multiple sclerosis, and four adults who have previously had a stroke, participated in the study by walking overground and on a treadmill. Kinematic data for heel and toe markers were collected at 60 Hz using a six-camera motion analysis system. The first algorithm was a coordinate-based treadmill algorithm, which used the position of the foot marker in relation to the sacral marker. All peaks and valleys (IC and TO events) were found by $t_{IC} = (X_{heel} - X_{sacrum})_{max}$, $t_{TO} = (X_{toe} - X_{sacrum})_{min}$, which represents the maximal displacement of the heel and toe from the sacrum marker. The second algorithm used was a velocity-based treadmill algorithm, which used the changes of the X coordinate (path of forward progression) of the heel marker moving in a positive X direction during swing to a negative X direction at each IC. The frame at which the foot begins moving backward on the treadmill is labeled IC. Toe-off is labeled as the X component of the velocity vector for the toe or heel marker changes from negative to positive. For the healthy young adults, compared to GRF events, the maximal offset was three frames. Ninety-eight percent of all events were within two frames of the GRF (100% coordinate and 96% velocity). The authors concluded that the frame offset for an impaired population was higher than healthy (four frames vs. three frames). As the use of a treadmill is more prevalent in motion analysis labs, the implementation of these algorithms will be useful and efficient automatic event detection.

This literature explains the process that will be performed during the data collection. Understanding the best method in determining data that is the most functional and comparable state is crucial. After determining the heel strike and toe off for each successful stance phase, then kinematic data can be processed properly.

Conclusion

The aim of this study is to determine the effect of two ankle orthoses and ankle taping, when compared to controls, on lower extremity kinematics and running economy during continuous running activity. There have been numerous studies evaluating ankle orthoses and taping methods. No known studies have compared these external support methods during a continuous running activity, taking into account the entire gait cycle.

APPENDIX A:

TABLES & FIGURES

Table 1. Participant Characteristics (M ± SD)

Participants	Age (years)	Mass (kg)	Height (m)
Female (n=8)	24.38 ± 3.58	64.5 ± 6.77	1.66 ± 0.06
Male (n=5)	24.40 ± 3.36	78.3 ± 4.88	1.78 ± 0.02
Total (N=13)	24.73 ± 4.18	70.74 ± 9.24	1.72 ± 0.08

Table 2: Ankle Kinematics in Frontal Plane (Mean ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10 min)	Time 4 (15 min)	Time 5 (20 min)	Time 6 (25 min)	Time 7 (30 min)
Ankle INV/EV Excursion								
	AA	18.52 ± 5.79*	19.15 ± 5.49*	19.75 ± 5.33*	19.05 ± 5.67*	19.15 ± 5.21*	19.29 ± 5.33*	19.35 ± 5.38*
	ASO	16.91 ± 4.80†	17.49 ± 5.62*	16.88 ± 6.09*	18.10 ± 6.06*	17.92 ± 6.12*	18.12 ± 6.06*	20.80 ± 10.3
	T	17.05 ± 5.90†	16.33 ± 5.86†	16.67 ± 5.85†	16.68 ± 6.04†	17.74 ± 6.14†	17.92 ± 6.33†	17.92 ± 6.35†
	C	25.32 ± 8.84	26.08 ± 8.74	26.67 ± 8.84	26.67 ± 8.84	26.89 ± 9.05	26.86 ± 9.31	26.92 ± 8.91
Ankle INV/ EV Position at IC								
	AA	6.43 ± 6.60*	6.12 ± 6.94*	7.57 ± 6.58*	6.13 ± 7.10*	6.38 ± 7.19*	6.70 ± 7.47*	5.92 ± 7.17*
	ASO	6.30 ± 9.90	5.53 ± 9.17	6.26 ± 9.29	5.94 ± 9.01	5.79 ± 8.89	6.63 ± 9.73	5.90 ± 10.97
	T	7.34 ± 11.96	6.87 ± 11.28	7.28 ± 11.02	7.19 ± 10.86	7.21 ± 11.16	7.12 ± 11.28	8.10 ± 11.34
	C	11.26 ± 6.97	11.45 ± 6.30	11.20 ± 6.38	11.10 ± 6.22	10.98 ± 6.54	10.66 ± 6.47	10.37 ± 7.37
Ankle Max INV								
	AA	10.32 ± 5.79*	10.50 ± 5.45*	10.73 ± 5.19*	9.75 ± 6.32*	10.32 ± 6.05*	9.93 ± 6.38*	10.11 ± 5.36*
	ASO	10.57 ± 8.15	10.27 ± 7.95	10.59 ± 8.59	10.89 ± 8.14	10.51 ± 8.04	11.34 ± 8.29	10.62 ± 8.38
	T	10.99 ± 12.51	10.34 ± 11.72	10.87 ± 11.74	10.42 ± 11.31	10.95 ± 11.67	11.22 ± 11.54	11.39 ± 11.79
	C	15.38 ± 6.08	15.49 ± 5.57	15.55 ± 5.70	15.38 ± 5.75	15.06 ± 6.10	14.89 ± 5.82	15.85 ± 6.36
Ankle Max EV Velocity								
	AA	177.94 ± 61.55*	178.32 ± 61.68*	202.70 ± 78.06*	199.19 ± 79.71*	191.99 ± 75.20*	193.46 ± 71.80*	192.46 ± 67.70*
	ASO	168.09 ± 45.21*	163.56 ± 42.33*	166.18 ± 63.61*	167.13 ± 48.75*	174.88 ± 51.93*	177.44 ± 51.35*	217.94 ± 103.89
	T	178.17 ± 55.37*	166.35 ± 57.92*	169.92 ± 56.38*	170.31 ± 59.40*	162.68 ± 74.35*	181.04 ± 60.35*	196.90 ± 73.16*
	C	267.86 ± 125.76	285.62 ± 150.27	281.86 ± 137.67	284.32 ± 133.78	284.90 ± 127.55	283.28 ± 141.66	284.34 ± 140.68

Abbreviations: INV, inversion; EV, eversion; IC, initial contact. * Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

Table 3: Ankle Kinematics in Sagittal Plane (M ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10	Time 4 (15	Time 5 (20	Time 6 (25	Time 7 (30
Ankle Max PF								
	AA	10.89 ± 5.81	10.66 ± 3.92	10.87 ± 3.79	11.31 ± 3.98	10.97 ± 3.95	10.18 ± 4.21	10.40 ± 5.47
	ASO	6.48 ± 3.24*	6.60 ± 4.05*	6.11 ± 5.81*	6.88 ± 5.00*	6.62 ± 4.11*	6.25 ± 4.09*	5.89 ± 3.19*
	T	6.36 ± 6.02†	5.27 ± 5.48*	5.63 ± 5.12*	5.39 ± 5.83*	5.94 ± 5.75*	5.98 ± 5.44*	6.02 ± 5.63*
	C	13.31 ± 9.35	13.72 ± 10.65	13.89 ± 8.87	14.00 ± 9.54	12.53 ± 9.88	12.46 ± 9.42	12.92 ± 8.69
Ankle PF/DF Position at TO								
	AA	10.87 ± 5.79	10.33 ± 4.16	10.85 ± 3.78	11.29 ± 3.96	10.96 ± 3.95	10.18 ± 4.21	10.36 ± 4.54
	ASO	6.49 ± 3.24*	6.57 ± 4.08*	5.71 ± 6.91*	6.73 ± 5.36*	6.51 ± 4.37*	6.17 ± 4.25*	5.89 ± 3.19*
	T	6.05 ± 6.72†	4.94 ± 6.18*	5.00 ± 6.55*	4.95 ± 6.35*	5.67 ± 6.34*	5.74 ± 6.06*	5.60 ± 6.39*
	C	13.29 ± 9.58	13.50 ± 10.90	13.69 ± 8.82	13.72 ± 10.08	12.35 ± 10.22	12.33 ± 9.71	11.97 ± 10.46
Ankle Max PF Velocity								
	AA	416.87 ± 92.72	410.70 ±	416.45 ± 92.71	415.88 ± 91.51	400.79 ± 86.49	410.18 ± 93.35	398.96 ± 89.58
	ASO	373.70 ±	379.38 ±	372.33 ±	376.93 ±	370.05 ±	367.39 ±	371.05 ± 83.16
	T	364.88 ±	354.59 ±	354.84 ±	356.59 ±	359.96 ±	352.41 ±	363.21 ± 93.64
	C	421.19 ± 89.52	416.52 ± 96.66	417.48 ± 81.52	414.73 ± 87.51	411.74 ± 84.30	402.64 ± 89.46	396.88 ±
Ankle Max DF Velocity								
	AA	285.05 ± 38.29	288.46 ± 45.47	291.72 ± 45.25	299.14 ± 51.28	292.39 ± 48.37	296.65 ± 51.68	297.65 ± 48.74
	ASO	275.08 ± 41.73	278.97 ± 37.21	275.85 ± 35.90	278.15 ± 35.19	275.74 ± 40.53	267.94 ± 47.36	272.26 ± 49.40
	T	271.54 ±	272.26 ±	273.60 ±	274.82 ±	276.17 ±	274.83 ±	276.17 ± 51.65
	C	294.36 ± 59.22	297.36 ± 53.72	306.18 ± 57.69	301.74 ± 45.71	303.44 ± 46.24	300.31 ± 52.01	302.53 ± 60.29

Abbreviations: PF, plantarflexion; DF, dorsiflexion; TO, toe-off. * Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

Table 4: Ankle Kinematics in Transverse Plane (M ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10	Time 4 (15	Time 5 (20	Time 6 (25	Time 7 (30
Ankle IR/ ER Position at IC								
	AA	3.03 ± 10.80	3.90 ± 9.25	3.36 ± 9.82	4.27 ± 9.12	4.07 ± 9.09	3.62 ± 9.50	4.40 ± 8.06
	ASO	5.48 ± 11.51	5.76 ± 10.20	4.04 ± 9.71	5.81 ± 9.69	5.51 ± 10.14	5.80 ± 10.08	6.03 ± 10.03
	T	6.28 ± 10.39*	6.83 ± 10.24*	6.72 ± 10.15*	7.22 ± 9.88*	7.54 ± 10.10*	7.35 ± 10.34*	7.24 ± 10.97*
	C	2.97 ± 9.38	2.19 ± 8.73	2.68 ± 9.06	2.52 ± 8.38	2.92 ± 9.07	3.80 ± 8.62	3.09 ± 8.74
Ankle IR/ ER Position at TO								
	AA	2.37 ± 7.47	5.10 ± 6.60	2.48 ± 7.34	1.75 ± 7.31	3.62 ± 6.39	2.37 ± 5.66	4.39 ± 6.65
	ASO	6.17 ± 8.91	6.06 ± 8.27	5.61 ± 6.78	6.00 ± 6.83	6.11 ± 8.04	6.45 ± 7.20	6.95 ± 7.81
	T	8.41 ± 8.56*	8.33 ± 8.56*	8.12 ± 7.57*	9.34 ± 9.24*	8.99 ± 7.82*	9.27 ± 8.77*	7.94 ± 9.94
	C	2.09 ± 6.59	1.35 ± 6.01	2.59 ± 5.64	1.61 ± 7.19	1.73 ± 8.58	2.56 ± 7.93	2.49 ± 6.93
Ankle IR/ ER Excursion								
	AA	21.70 ± 7.45	20.91 ± 6.63	21.14 ± 5.74	20.59 ± 5.84	19.90 ± 5.93	21.34 ± 7.21	20.38 ± 4.98
	ASO	18.20 ± 4.34*	17.61 ± 4.08*	18.73 ± 5.14*	18.03 ± 4.32*	17.46 ± 4.52*	17.75 ± 4.24*	17.36 ± 4.79*
	T	16.35 ± 3.78*	15.41 ± 2.87*	15.47 ± 2.54*	15.39 ± 3.08*	15.92 ± 2.85*	15.28 ± 3.02*	15.53 ± 3.14*
	C	22.53 ± 7.79	22.73 ± 8.26	22.52 ± 8.55	22.60 ± 8.93	21.94 ± 8.48	21.38 ± 8.12	23.08 ± 8.83
Ankle Max IR								
	AA	1.08 ± 8.80	0.34 ± 7.64	1.25 ± 7.68	0.54 ± 7.28	0.01 ± 7.50	1.02 ± 6.93	0.11 ± 6.12
	ASO	2.56 ± 9.80*	2.92 ± 8.88*	1.04 ± 8.37*	2.65 ± 8.32*	2.89 ± 9.19*	2.34 ± 8.49*	2.83 ± 8.61*
	T	3.99 ± 8.93*	4.59 ± 8.71*	4.22 ± 8.84*	4.72 ± 8.64*	4.77 ± 8.55*	4.95 ± 9.40*	3.55 ± 9.11
	C	1.08 ± 6.50	2.27 ± 5.69	2.08 ± 6.04	2.03 ± 6.24	1.37 ± 7.25	0.44 ± 7.06	1.55 ± 7.29
Mean Foot Progress Angle								
	AA	5.35 ± 1.86*	5.29 ± 2.01*	5.36 ± 2.02*	5.80 ± 2.10*	5.63 ± 2.36*	5.58 ± 2.33†	5.43 ± 2.11†
	ASO	5.46 ± 1.66*	5.62 ± 1.85*	5.78 ± 2.09*	5.65 ± 1.83*	5.88 ± 2.01*	5.76 ± 1.93*	6.02 ± 2.03
	T	5.09 ± 1.73†	5.54 ± 2.01*	5.56 ± 2.06*	5.73 ± 2.56*	5.89 ± 2.22*	6.07 ± 2.77*	5.86 ± 2.45*
	C	6.32 ± 1.78	6.59 ± 2.11	6.60 ± 2.03	6.67 ± 1.94	7.15 ± 2.19	6.96 ± 2.64	6.63 ± 2.10

Abbreviations: IR, internal rotation; ER, external rotation; IC, initial contact; TO, toe-off. * Significance at $p < 0.05$ compared to control; † Significance at $p < 0.001$ compared to control

Table 5: Knee Kinematics in Sagittal Plane (M ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10 min)	Time 4 (15 min)	Time 5 (20 min)	Time 6 (25 min)	Time 7 (30 min)
Knee Flex/ Ext Excursion								
	AA	30.71 ± 4.52	31.99 ± 4.57	31.96 ± 4.75	32.51 ± 4.03	31.64 ± 3.57	32.53 ± 4.39	31.85 ± 5.23
	ASO	29.36 ± 4.81	29.94 ± 5.22	30.16 ± 4.77	31.27 ± 5.02	31.44 ± 5.14	31.59 ± 4.85	31.60 ± 5.33
	T	28.52 ± 4.45*	28.78 ± 4.05*	29.71 ± 5.20	30.13 ± 4.61	30.10 ± 4.42	30.06 ± 4.70	31.59 ± 3.78
	C	30.97 ± 5.39	30.59 ± 4.24	30.51 ± 5.09	31.64 ± 3.57	31.89 ± 4.82	31.78 ± 5.48	32.10 ± 4.78
Knee Max Flex Velocity								
	AA	399.78 ± [illegible]	422.55 ± [illegible]	426.73 ± [illegible]	431.08 ± [illegible]	412.54 ± [illegible]	434.32 ± [illegible]	432.65 ± [illegible]
	ASO	390.16 ± [illegible]	405.55 ± [illegible]	395.27 ± [illegible]	400.48 ± [illegible]	414.27 ± [illegible]	417.28 ± [illegible]	411.86 ± [illegible]
	T	370.86 ± 47.75*	387.60 ± 77.06*	389.84 ± 76.59*	393.65 ± 84.96*	394.46 ± 77.35*	407.18 ± 90.81*	411.77 ± 97.28
	C	412.53 ± [illegible]	422.23 ± [illegible]	420.32 ± [illegible]	438.11 ± [illegible]	436.30 ± [illegible]	441.81 ± [illegible]	428.93 ± [illegible]

Abbreviations: Flex, flexion; Ext, extension. * Significance at $p < 0.05$ compared to controls

Table 6: Knee Kinematics in Transverse Plane (M ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10 min)	Time 4 (15 min)	Time 5 (20 min)	Time 6 (25 min)	Time 7 (30 min)
Knee Max IR								
	AA	17.82 ± 7.44	16.86 ± 6.16	17.21 ± 6.57	17.39 ± 5.98	17.35 ± 5.91	18.73 ± 6.41	17.30 ± 6.39
	ASO	14.77 ± 6.50	15.19 ± 6.24	15.66 ± 6.45	15.78 ± 6.53	15.93 ± 6.43	16.23 ± 6.50	16.69 ± 6.92
	T	11.79 ± 4.91*	12.15 ± 4.56*	12.63 ± 4.78*	12.52 ± 4.65*	12.85 ± 4.63*	13.03 ± 4.82*	14.13 ± 5.26
	C	16.31 ± 5.96	16.57 ± 6.04	16.58 ± 6.57	17.15 ± 5.95	17.15 ± 6.05	17.42 ± 6.25	17.67 ± 6.71
Knee Max IR Velocity								
	AA	248.58 ± 97.890	253.24 ± 105.06	254.65 ± 101.45	266.36 ± 101.10	273.09 ± 118.12	291.63 ± 115.53	292.14 ± 137.25
	ASO	216.34 ± 58.95	236.14 ± 69.75	267.95 ± 83.41	251.24 ± 85.34	262.26 ± 90.33	273.50 ± 79.36	274.33 ± 97.61
	T	190.27 ± 60.87*	214.58 ± 84.06*	225.79 ± 92.74*	227.69 ± 81.67*	233.48 ± 96.05*	255.34 ± 120.08*	247.55 ± 107.08*
	C	264.90 ± 105.85	275.68 ± 86.200	299.79 ± 90.830	305.81 ± 111.86	307.86 ± 105.21	315.31 ± 114.36	324.33 ± 138.41

Abbreviations: IR, internal rotation. * Significance at $p < 0.05$ compared to controls

Table 7: Hip Kinematics in Frontal Plane (M ± SD)

	Condition	Time 1 (0 min)	Time 2 (5 min)	Time 3 (10 min)	Time 4 (15 min)	Time 5 (20 min)	Time 6 (25 min)	Time 7 (30 min)
Hip ABD/ADD Position at IC								
	AA	5.08 ± 2.73*	5.42 ± 3.00*	6.33 ± 2.46*	6.36 ± 2.30*	6.46 ± 2.38*	6.34 ± 2.26*	6.59 ± 2.24*
	ASO	5.43 ± 3.42*	5.51 ± 3.99*	5.65 ± 3.05*	5.63 ± 3.51*	5.95 ± 3.78*	5.95 ± 4.20*	5.94 ± 3.57*
	T	5.16 ± 3.57*	6.04 ± 3.52*	6.23 ± 3.45*	6.03 ± 3.35*	6.03 ± 3.25*	6.46 ± 2.99*	5.90 ± 3.51
	C	3.79 ± 3.64	4.39 ± 3.57	4.24 ± 3.44	4.47 ± 3.58	4.69 ± 3.54	4.98 ± 4.16	4.56 ± 3.84
Hip Excursion (IC to Max ABD)								
	AA	7.86 ± 2.99	9.02 ± 3.00	9.00 ± 3.08	9.12 ± 3.15	9.15 ± 3.35	9.12 ± 2.77	9.59 ± 3.03
	ASO	8.80 ± 2.75*	8.82 ± 3.56*	9.00 ± 3.47*	8.94 ± 3.53*	8.65 ± 3.71*	8.95 ± 3.24*	9.02 ± 3.81*
	T	8.05 ± 3.34	8.49 ± 2.92	9.34 ± 3.36	8.57 ± 3.56	8.26 ± 3.71	8.86 ± 3.08	8.42 ± 3.57
	C	7.46 ± 3.85	8.25 ± 3.99	8.04 ± 3.78	8.16 ± 4.20	8.14 ± 3.78	8.17 ± 4.71	8.02 ± 4.00
Hip Mean ABD Velocity								
	AA	23.44 ± 10.71	27.85 ± 10.71	27.34 ± 10.18	28.11 ± 9.67	27.74 ± 10.65	27.34 ± 9.17	28.73 ± 10.18
	ASO	26.90 ± 9.47*	27.31 ± 12.73*	27.58 ± 10.87*	27.34 ± 10.59*	27.55 ± 11.07*	28.47 ± 14.01*	28.59 ± 10.72*
	T	26.25 ± 10.39	26.15 ± 9.01	28.44 ± 11.08	26.94 ± 10.36	25.91 ± 10.88	26.93 ± 9.59	26.08 ± 11.17
	C	21.79 ± 12.22	25.05 ± 11.45	23.27 ± 13.53	25.28 ± 11.10	25.96 ± 10.57	24.34 ± 13.38	24.66 ± 11.39

Abbreviations: ABD, abduction, ADD, adduction, IC, initial contact. * Significance at $p < 0.05$ compared to control

Figure 1: Ankle INV/EV Excursion (°)

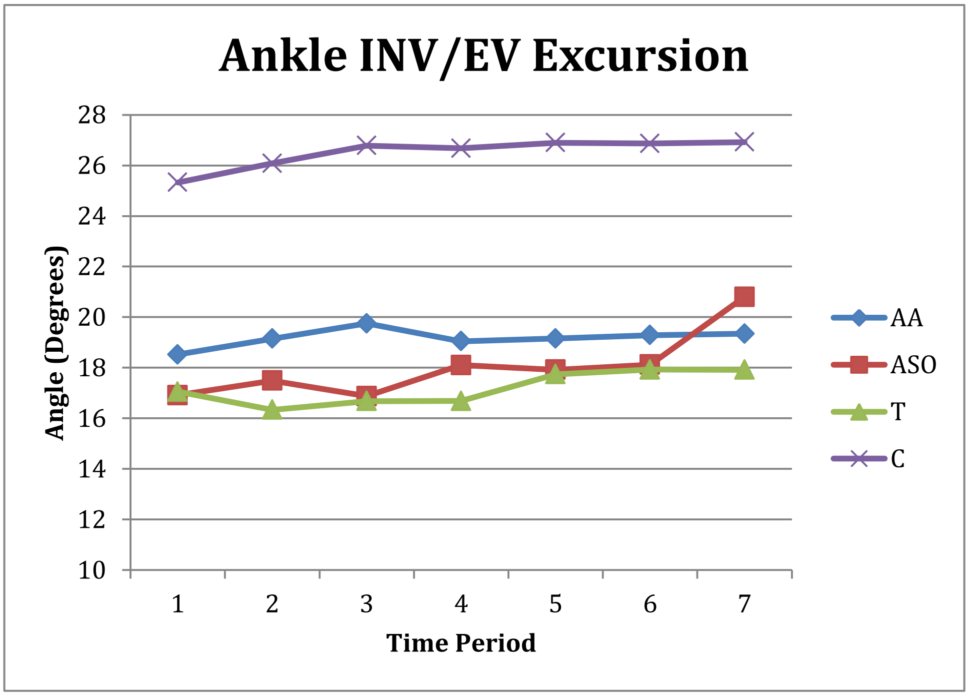


Figure 2: Ankle INV/EV at IC (°)

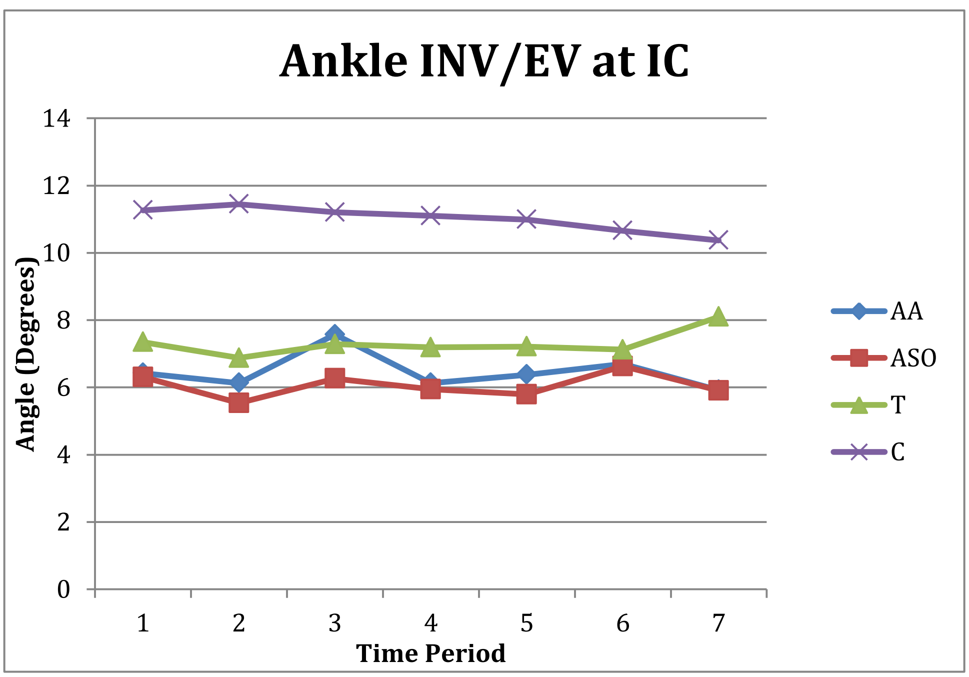


Figure 3: Ankle Max INV (°)

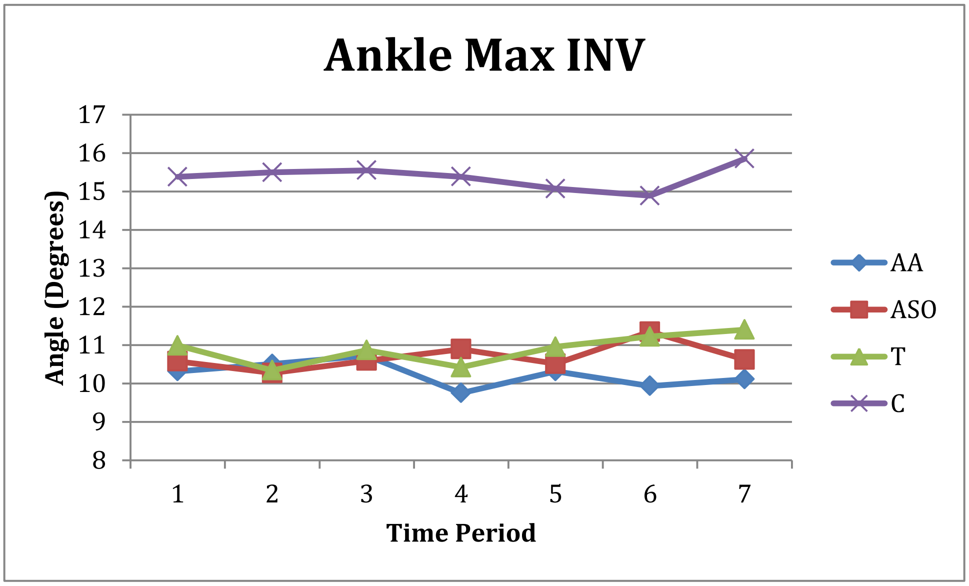


Figure 4: Ankle Max EV Velocity (°/s)

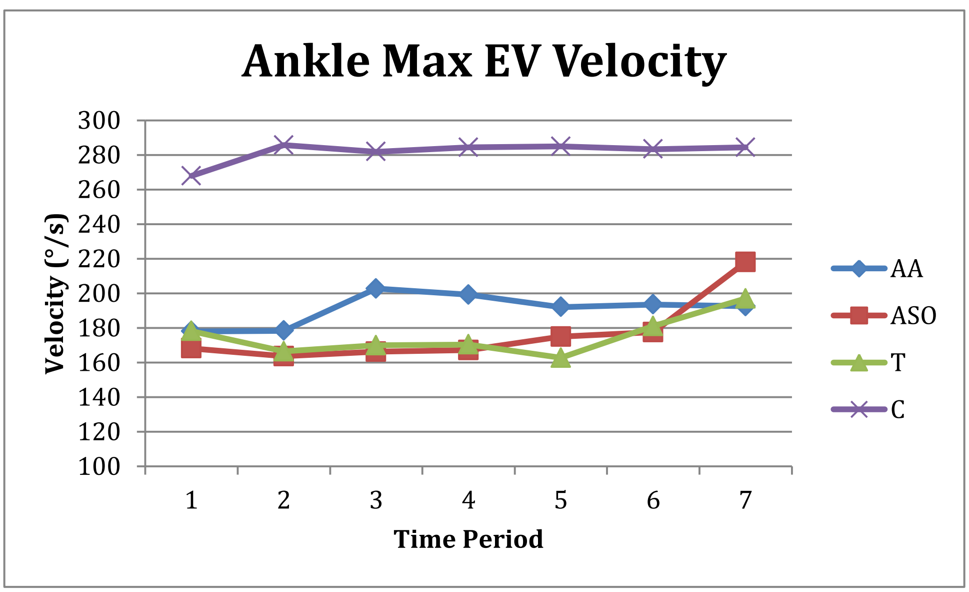


Figure 5: Ankle Max PF (°)

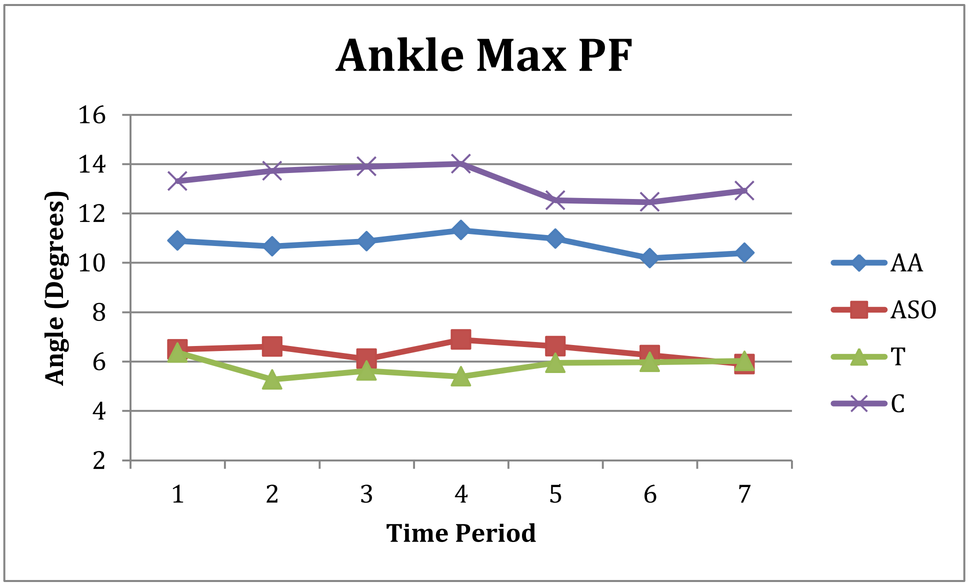


Figure 6: Ankle PF/DF at TO (°)

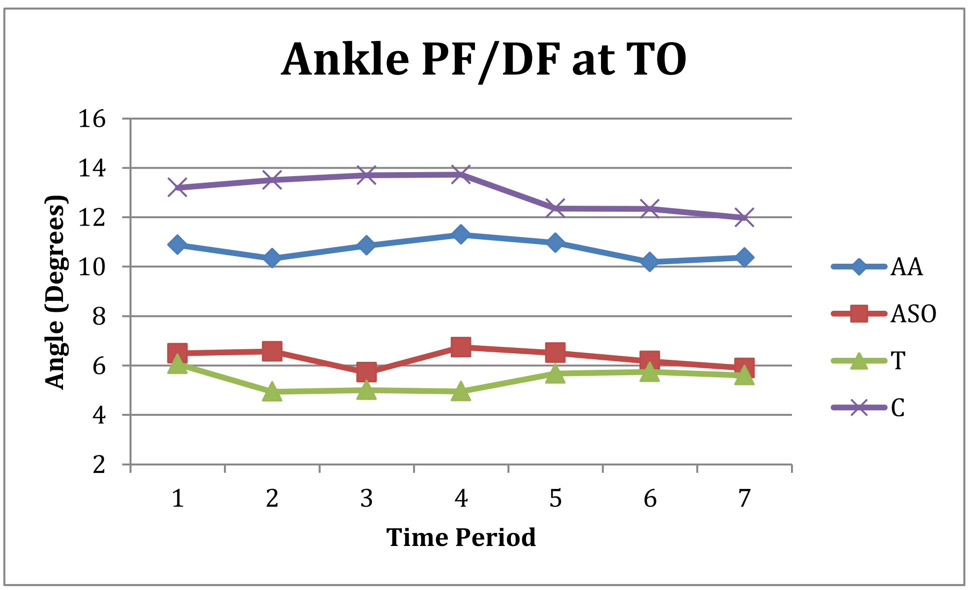


Figure 7: Ankle Max PF Velocity (°/s)

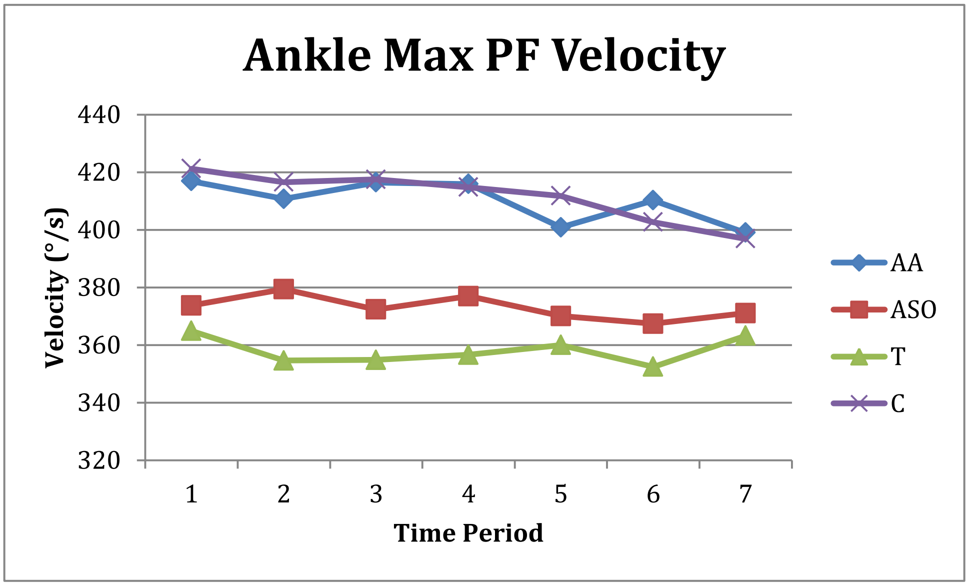


Figure 8: Ankle Max DF Velocity (°/s)

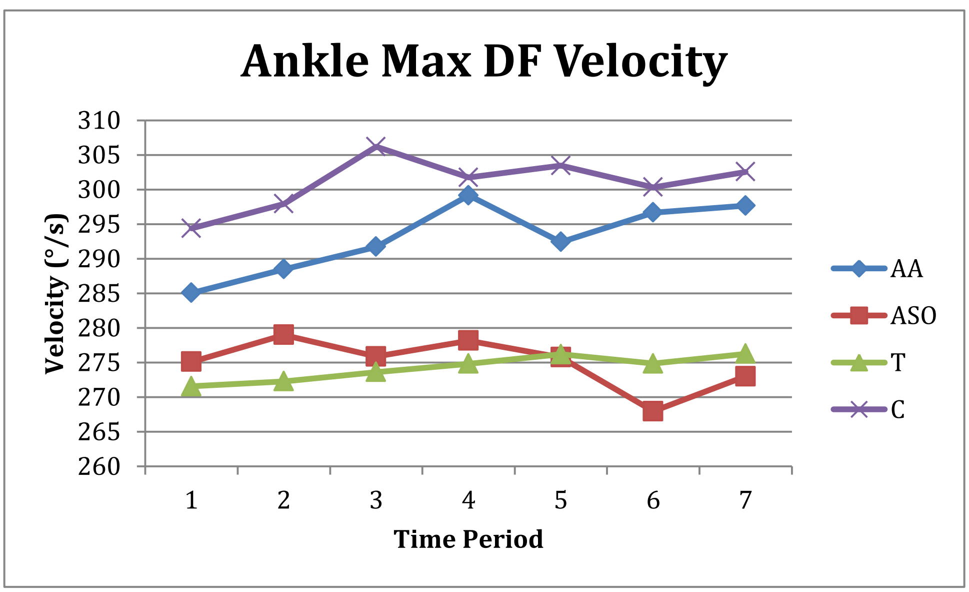


Figure 9: Ankle IR/ER at IC (°)

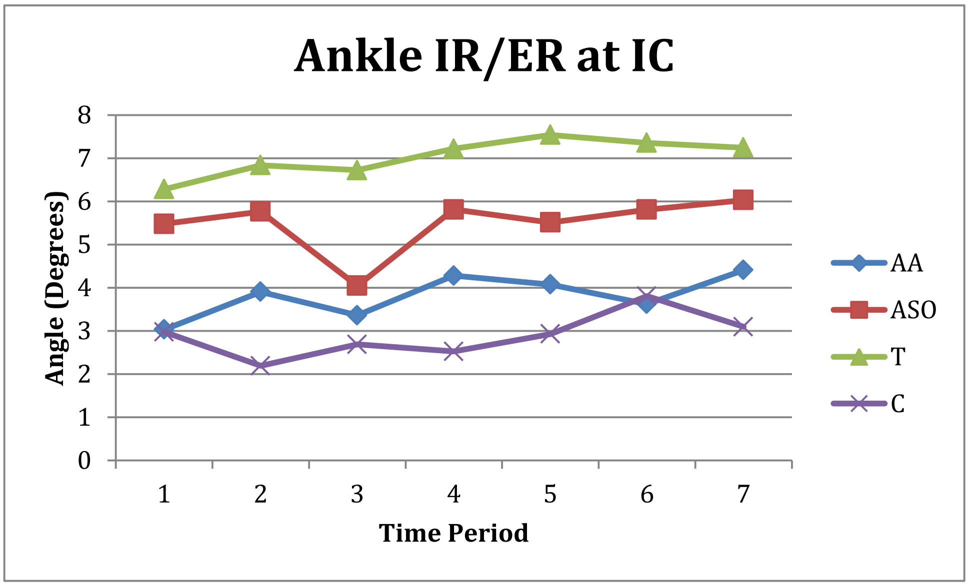


Figure 10: Ankle IR/ER at TO (°)

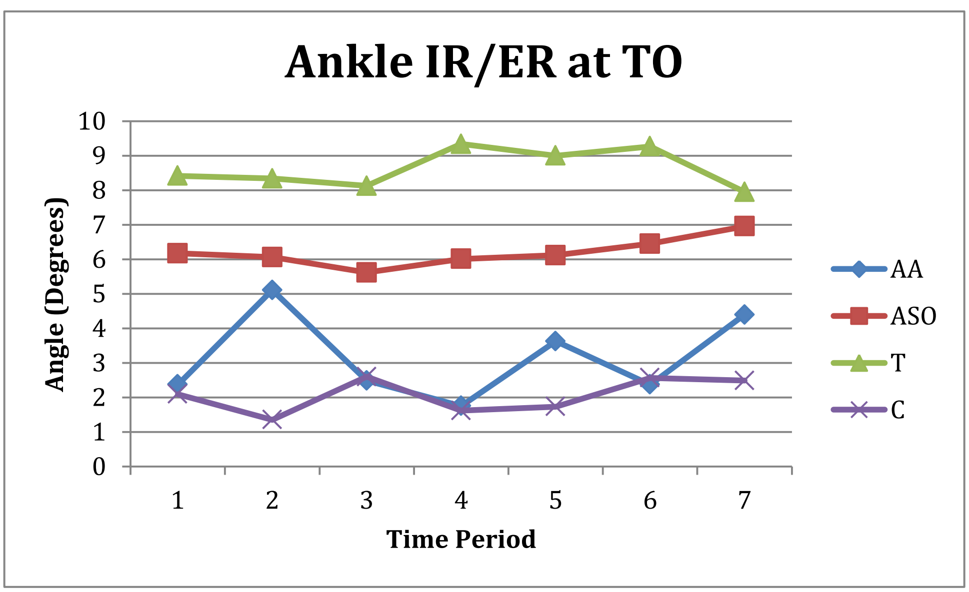


Figure 11: Ankle IR/ER Excursion (°)

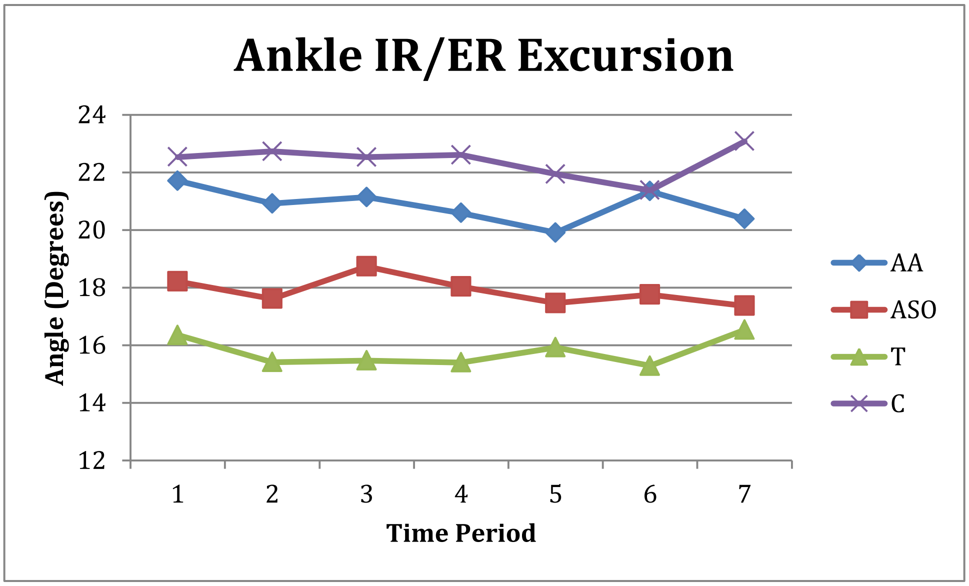


Figure 12: Ankle Max IR (°)

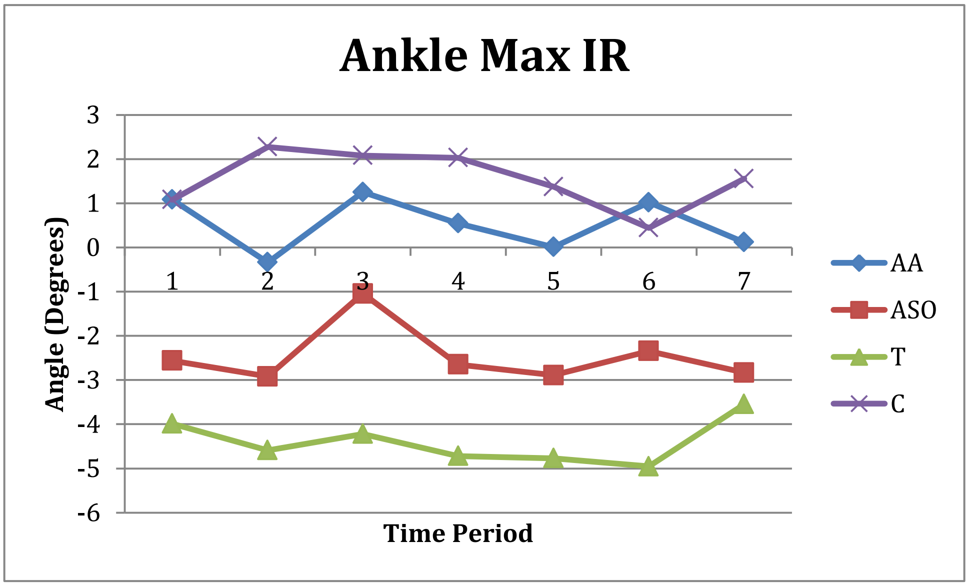


Figure 13: Mean Foot Progression Angle at Stance (°)

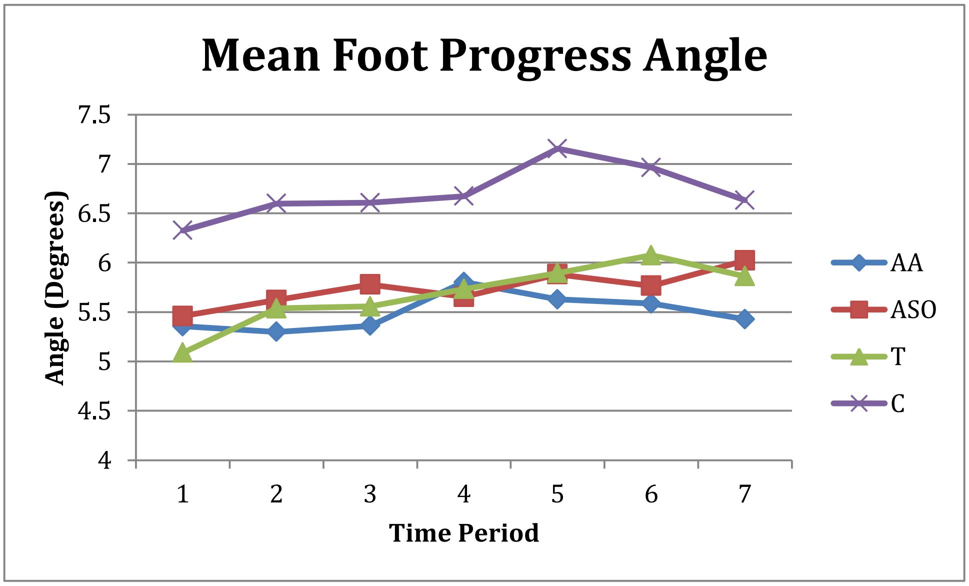


Figure 14: Knee Flexion Velocity (°/s)

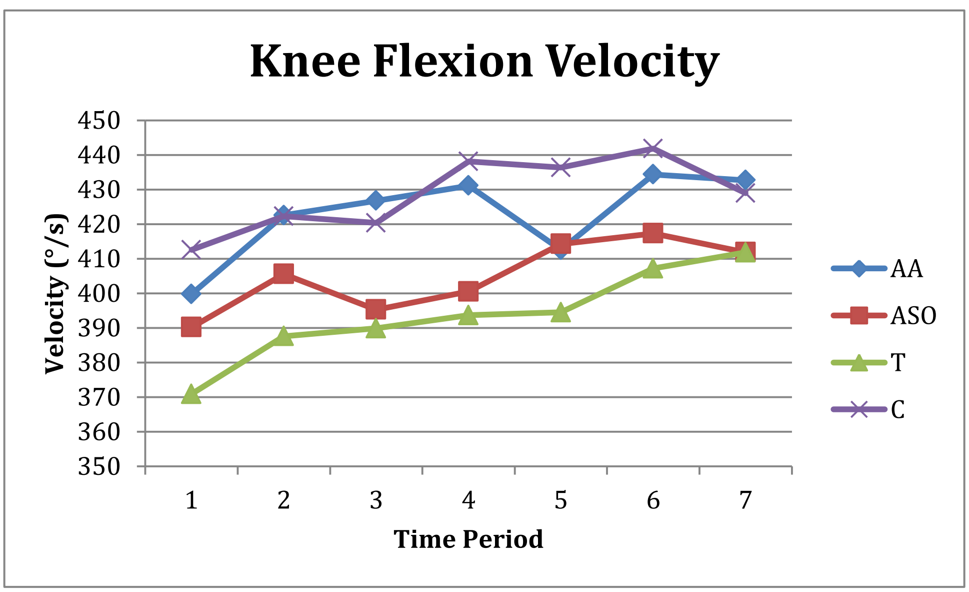


Figure 15: Knee Max IR (°)

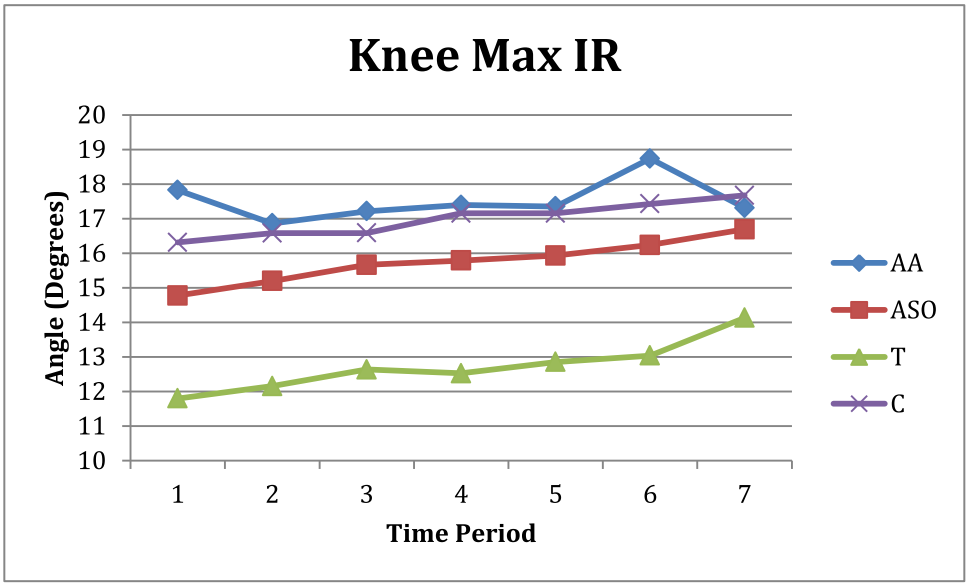


Figure 16: Knee Max IR Velocity (°/s)

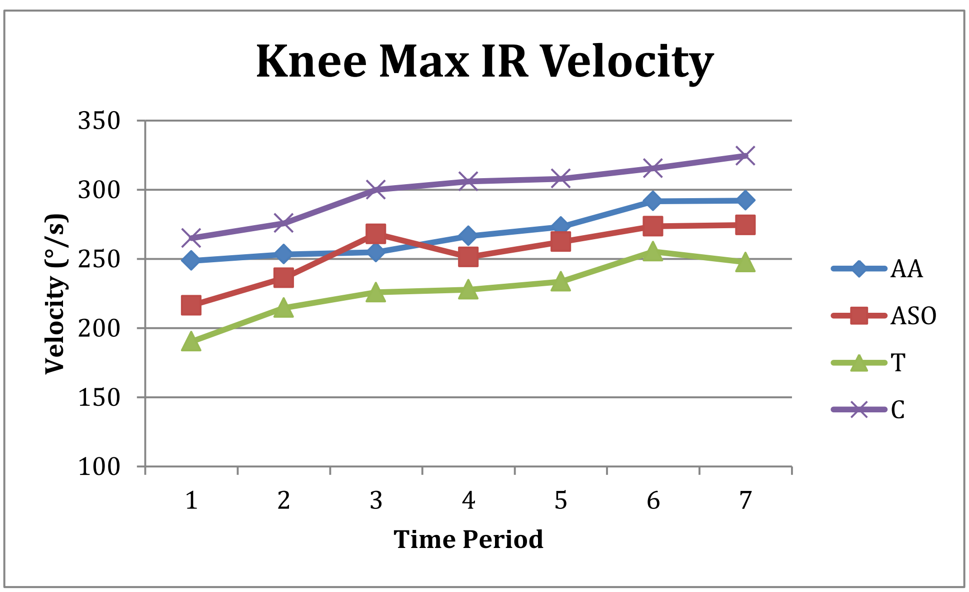
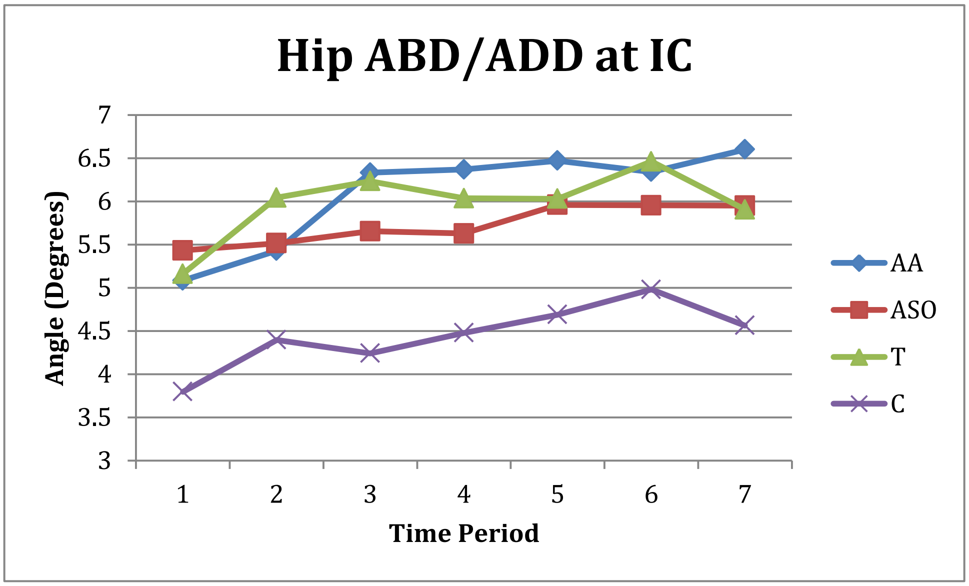


Figure 17: Hip ABD/ADD at IC (°)



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[1-20, 23-27, 29-35, 58, 59, 63-65]