On the Mechanics of the Ankle in the Stance Phase of the Gait

Kamran Shamaei, Massimo Cenciarini, and Aaron M. Dollar, *Members, IEEE*

***Abstract*—In this paper we explore the mechanical behavior of the ankle in the progression stage of stance during normal walking. We show that the torque/angle behavior of the ankle during this stage can be approximated by an augmented linear torsional spring. The mechanical parameters completely specifying this spring are identified, including stiffness, amount of rotation, and angle of zero moment. The effect of load weight, gait speed and ground slope on those parameters and the propulsive work of the ankle are also discussed. The findings of this paper can be applied to the design of leg orthoses, prostheses and exoskeletons, and bipedal robots in general, allowing the implementation of human-like leg compliance during stance with a relatively simple latched-spring mechanism.**

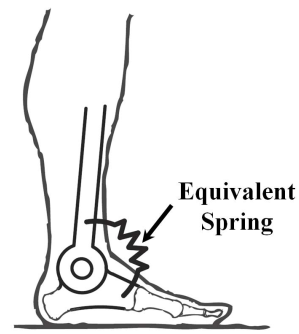

Figure 1. Ankle behavior can be approximated by a linear torsional spring in the progression stage of the stance phase of normal gait.

I. Introduction

SEVERAL engineering fields desire to replicate or approximate human gait mechanics using simple mechanical components. These include anthropomorphic bipedal robots (e.g. [1] and [2]), leg exoskeletons and orthoses ([3] and [4]), and lower-limb prostheses [5]. In terms of the ankle joint, moment-angle analysis of the stance phase of human walking shows a nearly linear relationship in the controlled dorsi-flexion and plantar-flexion stages of the stance phase ([6] and [7]). Therefore, it is speculated that a substantial amount of the function of the ankle joint during stance can be replaced by a linear torsional spring employed in the design of the ankle orthosis/prosthesis.

Along these lines, the most common modern ankle-foot prostheses employ a single spring in their design, such as a carbon fiber leaf spring [8]. The gait of an amputee who uses these passive compliant prostheses approximately mimics the unaffected ankle during normal walking, but deviates from normal as walking speed increases [5].

In passive ankle-foot orthoses (AFOs), a solid plastic shell is most typically employed to stabilize the flexion/extension motion when needed [8]. However, these stiff devices highly diminish the propulsive abilities of the subject and lead to inefficient gait. In addition, researchers have developed active pneumatic orthoses for assistance with gait [9] and quasi-passive orthoses for control of drop-feet [10]. Part of the motivation for the analysis presented in this paper is to enable the authors to work towards appropriately-tuned quasi-passive compliant ankle-foot orthoses that will assist with the gait of the wearer in stance and allow free movement of the ankle in swing.

Previous efforts have explored the dynamics of the ankle joint, including active and passive mechanics ([11]- [14]). These works extract the mechanics of the ankle (passive/active elastic, inertia, and viscous parameters) at different angles and muscle activation levels, using system identification techniques. Since the ankle experiences complex loading conditions and movement pattern in walking, the findings of these researchers could not be directly used in the design of orthoses/prostheses.

The moment-angle relationship and stiffness of the lower extremity joints has been investigated in different instants of the gait [15]. Other researchers have investigated the mechanics of the ankle in the stance phase of the gait. The slope of a linear fit in the controlled dorsi-flexion phase of stance is used to evaluate pediatric and impaired gait [7]. This slope is referred to as the quasi-stiffness of the ankle in the corresponding phase. The sagittal plane mechanics of the ankle in walking is investigated in [6], which shows that the quasi-stiffness of the ankle increases as the gait speed increases. The authors suggest that passive components cannot completely explain the behavior of the ankle.

While these previous efforts investigate a number of aspects of the ankle mechanics, they do not present a range of quasi-stiffness of the ankle joint for different gaits that could be used in the design of orthoses and prostheses.

The work presented in this paper examines the linear spring-like behavior of the ankle during normal level-ground gait and can be used to motivate the choice of mechanical stiffness in the design of devices such as ankle-foot orthoses and prostheses. We begin with an explanation of the mechanical parameters that are used in this paper. Next, these parameters are obtained for different subjects from the open literature and the behavior of the ankle of most of these subjects is shown to approximate a linear torsional spring,

This work was supported in part by the US Army Natick Soldier Research Development and Engineering Center, contract #W911NF-07-D-0001 and the US Defense Medical Research Development Program, contract #W81XWH-11-2-0054.

K. Shamaei, M. Cenciarini, and A.M. Dollar are with the School of Engineering and Applied Science, Department of Mechanical Engineering and Materials Science, Yale University, New Haven, CT 06511 USA (e-mail: {kamran.shamaei, massimo.cenciarini, aaron.dollar}@yale.edu).

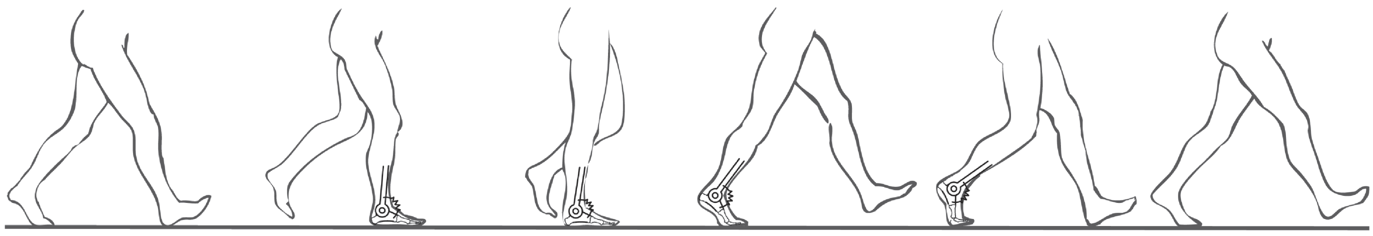

Figure 2. The ankle undergoes four arcs of motion in one cycle of the gait: Controlled plantar and dorsi flexion, powered plantar-flexion and swing dorsi-flexion

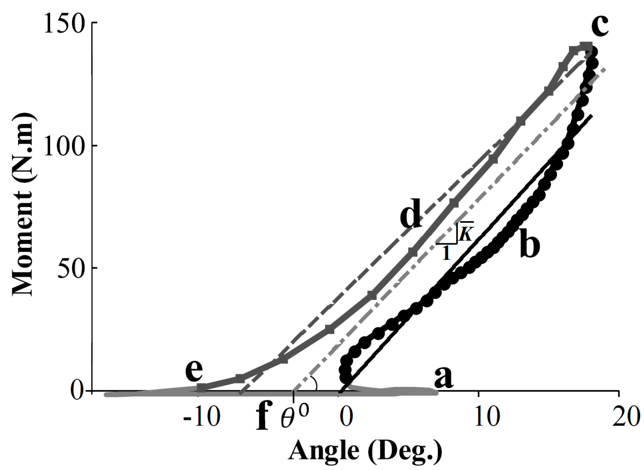

Figure 3. The moment-angle graph of ankle in one gait cycle for a subject with a normal gait (data from [18]).

which is augmented for the high load weights, gait speeds, and sloped surfaces. Finally, the variability of the ankle mechanics in the stance phase is investigated with respect to the changes in load weight, gait speed, and ground slope.

II. Methods

A. Ankle in Stance Phase of the Gait

The ankle joint exhibits a small plantar-flexion within the first 10% of the gait cycle. The ankle joint, from 10% to 62% of the gait cycle, undergoes a critical progression stage in the stance phase of the gait that is composed of a dorsi-flexion mode (corresponding to the mid-stance phase [16]) and a plantar-flexion mode (corresponding to the terminal-stance phase [16]). At the end of the progression stage, the foot leaves the ground to start the swing phase. Different phases of the gait are illustrated in Fig. 2. The ankle generates huge torque (up to $2N.m/Kg$) and power (up to $6W/Kg$) in the progression stage that essentially contributes to the forward propulsion of the body [30]. Accordingly, the ankle-foot complex essentially requires assistance in this stage of the gait upon impairment in the musculoskeletal system. Thus, a proper design of orthotic and prosthetic devices requires deep understanding of the mechanical behavior of the ankle in this stage. This paper separately investigates the mechanical behavior of the ankle in the dorsi-flexion and plantar-flexion modes of the progression stage of the stance phase of the gait.

B. Data and Terminology

The moment-time and angle-time profiles of the ankle are obtained from the open literature including [17] – [29]. The moment and angle of the ankle are analyzed against each other. An example of the moment-angle graph is depicted in Fig. 3 (raw 5, data from [18]), with the instant of the onset and end of the dorsi-flexion and plantar-flexion modes indicated. The letters on Fig. 3 correspond to the phases shown on Fig. 2. The amount of flexion in dorsi-flexion mode (θ_{df}) and plantar-flexion mode (θ_{pf}) can be obtained by subtracting the initial angle from the final angle of that particular mode. The intersection of the moment-angle traces with the horizontal axis is defined as the angle of zero moment (θ_{df}^0 and θ_{pf}^0) for each mode. The angle of zero moment or equilibrium of the overall progression stage (θ^0) is defined as the mean of θ_{df}^0 and θ_{pf}^0. This parameter is shown on the graph of Fig. 3. The ankle generates its maximum moment (M_{max}) at the onset of the plantar-flexion (c in Fig. 3).

The characteristic stiffness of the ankle (equivalent to the dynamic stiffness defined in [7]) in dorsi-flexion (K_{df}) and plantar-flexion (K_{pf}) modes are defined as the slopes of the corresponding regression lines shown in Fig. 3. The overall characteristic stiffness of the progression stage ($\overline{K}$) is obtained by taking the mean of K_{df} and K_{pf}. The value of $\overline{K}$ is the slope of the equivalent line shown in Fig. 3. The propulsion work of one cycle of the gait (E) is the area enclosed by the moment-angle curve. Since the ankle power within the plantar-flexion of the first 10% of the gait and the swing phase is negligible, the value of E approximates the propulsive work of the ankle joint in the progression stage.

The physical and demographic properties of subjects and subject groups whose kinetic and kinematic data are employed are listed in Table I. These parameters include the mean weight ($\overline{W}, Kg$), mean gait speed/cadence ($\overline{V}$), mean age ($\overline{Age}$), mean height ($\overline{H}, m$), sex, and number of subjects in each group (n). The $Control$ parameter defines the corresponding parameter studied in the original text that allows the readers to identify the subject groups. The units of the parameters of the original texts are left intact. The reason is twofold: first, using the same units allows for comparison and avoids inconsistency. Second, in order to use identical units, the physical characteristics as well as the moment and angle time profiles of the individual subjects are required,

TABLE I
DEMOGRAPHIC PROPERTIES AND MECHANICAL PARAMETERS OF THE ANKLE OF THE SUBJECT SETS

	Properties of Subject Groups							Mechanical Parameters												
	$\overline{W}$	$\overline{V}$‡‡	$\overline{Age}$	$\overline{H}$	Sex	n	$Control$	K_{df}	K_{pf}	$\overline{K}$	θ_{df}	θ_{pf}	R^2_{df}	R^2_{pf}	θ^0_{df}	θ^0_{pf}	θ^0	M_{max}	E	Ref.
1†	76.8	99.8C	30.3	1.81	M	16	6kg	**373**	**347**	360	20	24	**88**	**97**	128	133	130.5	135	10.8	[17]
2†		100.6C					20kg	**454**	**396**	425	20	24	**86**	**98**	128	133	130.5	163	14.6	
3†		100.0C					33kg	**525**	**418**	471	19	24	**84**	**97**	124	136	130.0	166	17.9	
4†		102.4C					47kg	**559**	**443**	501	20	24	**82**	**98**	127	134	130.5	189	21.4	
5†	*	110C	*	*	F	1	WM22	**370**	**251**	310	15	34	**92**	**93**	0	17	8.5	140	18.4	[18]
6†	73.2	1.60S	28	1.75	*	1	LW	**394**	**646**	520	23	17	**87**	**96**	19	14	16.5	170	11.3	[19]
7†	79	1.21S	21	1.82	M	1	A	**344**	**346**	345	20	23	**99**	**100**	-9	-12	-10.5	137	6.2	[20]
8†	63	1.18S	26	1.76	M	1	B	**322**	**250**	286	15	24	**98**	**98**	0	-9	-4.5	104	14.6	
9†	56	1.40S	21	1.62	F	1	C	**183**	**214**	198	18	23	**95**	**99**	-11	-16	-13.5	84	5.2	
10†	67.2	1.15SS	23	1.75	M	1	A	**412**	**580**	496	21	17	**99**	**98**	-19	-15	-17.0	153	4.5	[21]
11†	70.0	1.44S	26	1.8	M	1	B	**422**	**483**	452	19	19	**84**	**96**	-17	-17	-17.0	154	3.8	
12†	84.3	1.43S	29	1.81	M	1	C	**89**	**474**	281	10	13	**16**	**99**	-17	-20	-18.5	99	3.0	
13‡	51.8	0.54S	12.9	*	F/M	8	V. Slow	**2.98**	**1.94**	2.46	23	33	**96**	**93**	-3	-17	-10.0	1.10	0.085	[22]
14‡		0.75S					Slow	**3.03**	**2.32**	2.67	24	25	**95**	**94**	-6	-11	-8.5	1.11	0.032	
15‡		1.15S					Free	**3.58**	**2.09**	2.83	21	33	**89**	**98**	-2	-18	-10.0	1.19	0.229	
16‡		1.56S					Fast	**4.40**	**2.35**	3.37	19	33	**87**	**99**	-4	-19	-11.5	1.25	0.257	
17‡	73.36	1.21NS	24	1.78	M/F	9	$-15°$	**2.72**	**4.30**	3.51	25	16	**99**	**94**	14	6	10.0	1.27	-0.193	[23]
18‡		1.24NS					$0°$	**5.29**	**4.84**	5.06	19	20	**98**	**94**	12	13	12.5	1.62	0.015	
19‡		1.31NS					$15°$	**6.55**	**5.38**	5.96	11	23	**63**	**97**	27	1	14.0	13.93	0.312	
20‡	76.7	*	27.2	1.80	M	26	*	**5.30**	**4.53**	4.91	13	20	**91**	**99**	-3	-10	-6.5	1.54	0.200	[24]
21‡	*	108C	*	*	M/F	15	Shoe	**4.14**	**4.04**	4.09	17	21	**85**	**99**	-8	-12	-10.0	1.52	0.153	[25]
22‡	68.5	110C	43.1	1.71	F/M	20	Adult	**4.47**	**2.15**	3.31	18	32	**90**	**99**	-24	-39	-31.5	1.31	0.276	[26]
23‡	41.4	124C	10.8	1.47	F/M	20	Young	**4.21**	**2.04**	3.12	16	29	**90**	**100**	-24	-37	-30.5	1.18	0.279	
24•	65.7	1.3S	27.3	1.73	M/F	8	no AS	**65.04**	**57.76**	61.40	15	20	**89**	**99**	1	-5	-2.0	19.52	2.52	[27]
25•	*	1.3S	*	*	M/F	40	*	**82.48**	**40.00**	61.24	9	22	**78**	**100**	-6	-19	-12.5	13.98	2.76	[28]
26••	72.7	1.30S	28.4	1.78	M	50	Male	**3.06**	**1.91**	2.48	13	24	**90**	**99**	-7	-18	-12.5	0.77	0.154	[29]
27••	59.84	1.34S	28.6	1.64	F	49	Female	**2.79**	**1.66**	2.22	15	28	**90**	**99**	-8	-21	-14.5	0.76	0.179	

†: Stiffness *(N.m/rad.)*, Moment (*N.m*), and Work (*J*)
‡: Stiffness (*N.m/kg.rad.*) , Moment (*N.m/kg*), and Work (*J/kg.*)
•: Stiffness (*%BW.LL./rad.*) and Moment (*%BW.LL.*)
••: Stiffness (*N.m/kg.m.rad.*) , Moment (*N.m/kg.m*), and Work (*J/kg.m*)
*: Not specified
‡‡: Cadence (*steps/min*), Speed (*m/sec.*), Normalized Speed *(m/m.s)*,
Notice that the subject groups are divided by the lines.

which is usually not the case. Indeed, the mean and standard deviation of the parameters and physical properties of the groups (rather than individuals) are often provided.

III. RESULTS

The spring-type behavior of the ankle in the progression stage of the stance phase is established in section III.A. It is shown that the spring-like behavior of the ankle diminishes as the load weight, gait speed, and amount of ground slope increase. Then, the variability of mechanical parameters of the ankle is investigated with respect to the load weight, gait speed, and ground slope in sections III.B-D.

A. Ankle as a Spring in the Progression Stage

The mechanical parameters of the ankle for 27 subjects and subject groups are listed in Table I. The values of coefficients of determination (R^2) of the linear regression is shown to be high for the normal gait speeds, zero load weights, and level grounds, both in dorsi-flexion and plantar-flexion modes (rows 5-12 and 20-27). Thus, the ankle can be acceptably characterized, from a mechanical point of view, by a linear torsional spring during the progression stage of the stance phase for the natural gait. Nevertheless, since the subjects exhibit propulsion work, the ankle joint would require augmentation in addition to a passive spring mechanism. This finding is along with the findings of [6] and [7]. Nevertheless, one should notice that the ankle joint exhibits a more linear behavior in the plantar-flexion mode as compared to the dorsi-flexion mode.

As the load weight increases (rows 1 to 4 of Table I), the value of R^2 of the dorsi-flexion mode decreases and the value of E increases. Fig. 4 shows that E linearly increases with as the load weight (W_L) increases. In a similar fashion, the value of R^2 decreases and E dramatically increases when the gait speed increases (rows 13 to 16 of Table I), as shown in Fig. 5. Therefore, the behavior of the ankle joint dramatically deviates from that of a spring for high load weights and fast gait speeds. Thus, the design of the ankle joint of an orthosis or a prosthesis should incorporate an active element to provide the propulsion energy in case of load carriage and fast gait. Additionally, the ankle joint exhibits a linear behavior in both dorsi-flexion and plantar flexion modes for level and downhill walking (row 17 and 18); yet, the ankle dissipates a considerable amount of energy in downhill walking. An uphill gait requires extensive amount of propulsive work, hence the behavior of the ankle joint deviates from a linear spring for a gait on sloped surfaces. The variability of the propulsive work with respect to the ground slope is shown in Fig. 6.

Consequently, a device (e.g. orthoses, exoskeletons, prostheses, and biped robots) or mechanical model can approximate the behavior of the human ankle by exploiting a spring with a suitable stiffness in conjunction with a power component and a damping mechanism in the progression stage and allowing free movement in the rest of the gait cycle.

Since realization of a variable stiffness mechanism is difficult to achieve, the value of ($\overline{K}$) is proposed as the spring constant of the envisioned device or model. The design of the device could alternatively choose the minimum value of K_{df} and K_{pf}. As such, the ankle is approximately modeled by a torsional spring with stiffness equal to the mean (minimum) of the stiffness of the dorsi-flexion and plantar-flexion modes. The characteristic stiffness of the ankle of the subject ranges from *90* to *580Nm/rad*. in level walking. If the ankle is modeled by a torsional spring during the progression stage, θ^0 would be the angle at which the spring is at its rest configuration (the angle at which the spring is engaged). Accordingly, maximum value of θ_{df} and θ_{pd} defines the magnitude of deflection of the spring in the corresponding mode.

If the design of orthosis/prosthesis includes an active component (an electric motor, a pneumatic cylinder, etc.), the power of the active component should be adjusted based on the load weight, gait speed, and ground slope. An energy dissipating mechanism could be further exploited in downhill walking and whenever the energy should be removed from the system.

B. *Ankle Mechanics with respect to Load Weight*

The characteristic stiffness of the ankle in the dorsi-flexion and plantar-flexion modes, and the entire progression stage exhibits a linear increase with respect to the load weight, as displayed in Fig. 7. The data (rows 1 to 4 of Table I) are primarily obtained from [17]. The amount of rotation remains approximately constant as the load (backpack) weight increases and the angle of zero moment does not show any notable change as the load weight changes. It is noticeable that the ankle behaves like a spring in the plantar-flexion mode independent of the weight. However, the behavior of the ankle in the dorsi-flexion mode deviates from linear in higher weights and the ankle is augmented. Therefore, assistance of the ankle in higher loads could require active assistance (such as that of a motor).

C. *Ankle Mechanics with respect to Gait Speed*

The characteristic stiffness of the ankle is plotted with respect to the gait speed in Fig. 8. The data (rows 13 to 16 of Table I) are primarily extracted from [22]. The speed of level walking of the subjects is categorized as very slow, slow, free, and fast. The characteristic stiffness of the dorsi-flexion and plantar-flexion modes and the overall characteristic stiffness of the progression stage are shown with black, dark gray, and light gray bars, respectively. The stiffness of the ankle in dorsi-flexion mode shows an increase with respect to the gait speed. It is noticeable that the mechanical behavior of the ankle in the dorsi-flexion mode becomes more non-linear (smaller R^2) at higher gait speeds and in plantar-flexion mode becomes more linear (greater R^2), which is along with the results of [31]. In fact, the ankle is augmented at higher speeds. Since, the data of individual subjects are not provided (rather the means and standard deviations of the treatment groups), an ANOVA could not be applied. Yet, a linear contrast of [-1.5 -0.5 0.5 1.5] results in a $p = 0.004$ for the dorsi-flexion mode. The

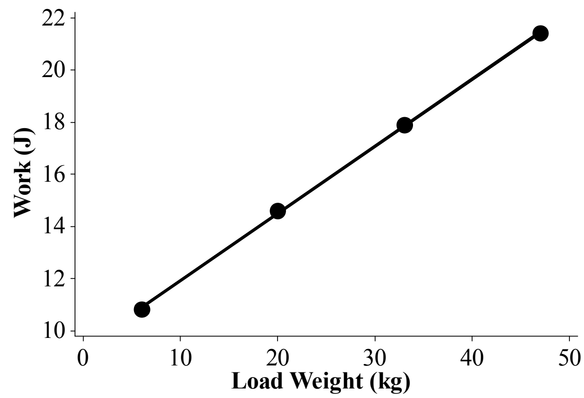

Figure 4. The propulsion work of the ankle in one cycle of the gait ($E = 9.34 + 0.258W_L, R^2 = 99.9\%, p = \{0.000,0.000\}$,) plotted against the load weight.

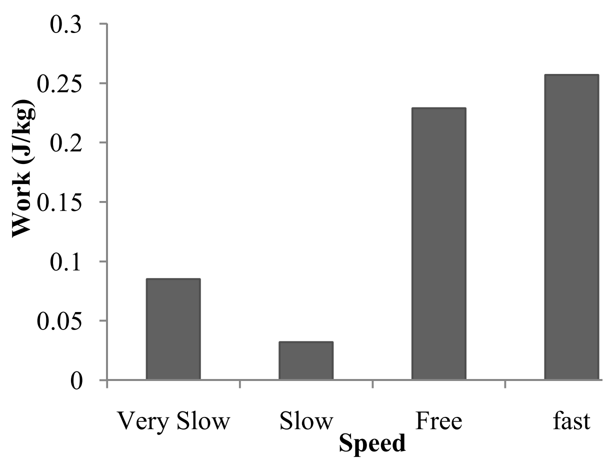

Figure 5. The propulsion work of the ankle in the stance phase of one cycle of the gait plotted against the gait speed.

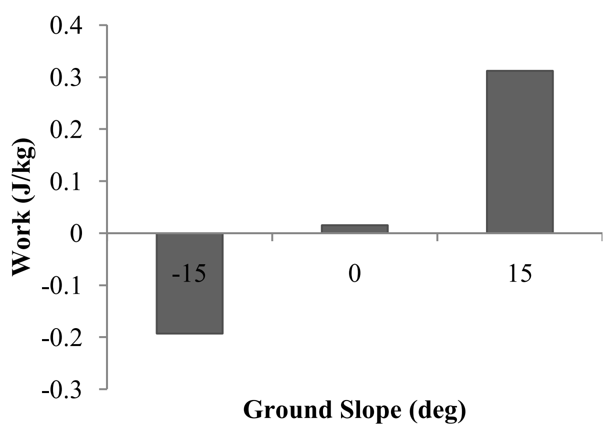

Figure 6. The propulsion work of the ankle in the stance phase of one cycle of the gait plotted against the ground slope.

characteristic stiffness of the ankle in plantar-flexion, however, does not exhibit a significant change with respect to the gait speed ($p = 0.168$). Furthermore, the amount of flexion and angle of zero moment of both dorsi-flexion and plantar-flexion modes do not show any notable change with respect to the gait speed.

D. Ankle Mechanics with respect to Ground Slope

The data (rows 17 to 19 of Table I) used in this section are primarily employed from [23]. The authors describe the changes of the kinetics and kinematics of the gait for different slopes including: $\{-39°, -15°, 0°, 15°, 39°\}$. The three middle ground slopes are employed here, because the mechanical behavior of the ankle dramatically deviates from that of a spring when walking on the highly sloped surfaces. Fig. 9 shows that the characteristic stiffness of the ankle in both modes increases as the ground slope increases. It is noticeable that the ankle provides a greater stiffness in the plantar-flexion mode in downhill walking, while it generates a greater stiffness in the dorsi-flexion mode in uphill walking. The value of θ_{df} decreases as the slope increases, which is in contrast to the decrease of θ_{pf}. The angle of zero moment, however, does not show a special trend of change with respect to the slope. Indeed, one may notice that the difference between the angle of zero moment in both modes increases as the slope deviates from zero. Therefore, more accurate model of the ankle in the progression stage of the gait on sloped surfaces should consider the behavior of the ankle separately in each mode, whereas a single spring would suffice modeling the ankle in the entire progression stage. Nevertheless, it should be noticed that the ankle has a closely linear behavior in downhill walking; whereas, uphill walking highly requires torque augmentation.

IV. CONCLUSIONS AND FUTURE WORK

This work focuses on the mechanics of the ankle in the progression stage of the stance phase of the gait and establishes the spring-type behavior of the ankle during this critical stage. Several mechanical parameters that accurately define the moment-angle behavior of the ankle in this stage are described and accordingly determined. Finally, the changes of the mechanical parameters of the ankle joint in the progression stage are investigated with respect to the load weight, gait speed and slope as three major parameters.

This paper suggests that devices that include ankle joint can employ a spring in their design with proper stiffness in order to approximate the behavior of ankle in level and downhill walking and assist with the gait in very slow to preferred walking speed and low load weights. This finding coincides with the findings of ([6] and [31]). Moreover, this paper suggests that the design of orthoses could incorporate a spring with proper stiffness for higher load weights and gait speeds to replace a portion of the ankle work. This paper further proposes that the stiffness of the device would ideally be adjusted based on the weight, speed, and slope of the ground. Finally, this paper investigates the amount of additional propulsive work that should accompany the passive spring of the device for a load carriage, high gait speed, and sloped ground.

The current work employs the kinetic and kinematic data of both the individual subjects and subject groups. The open literature does not provide a complete investigation of the gait data of the individual subjects under different gait speeds, slopes, and weights, and they mostly provide the means and standard deviations of the groups of individuals.

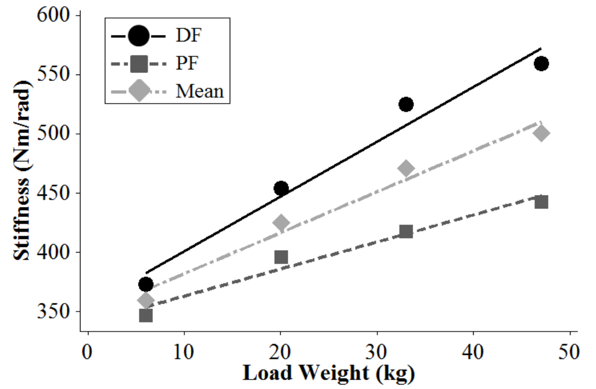

Figure 7. The characteristic stiffness of the ankle in dorsi-flexion ($K_{df} = 355 + 4.62W_L, R^2 = 97\%, p = \{0.002, 0.015\},$) and plantar-flexion ($K_{pf} = 209 + 2.399W_L, R^2 = 95\%, p = \{0.001, 0.018\}$) modes, and the progression stage ($\bar{K} = 348 + 3.45W_b$) of the gait plotted against the load weight.

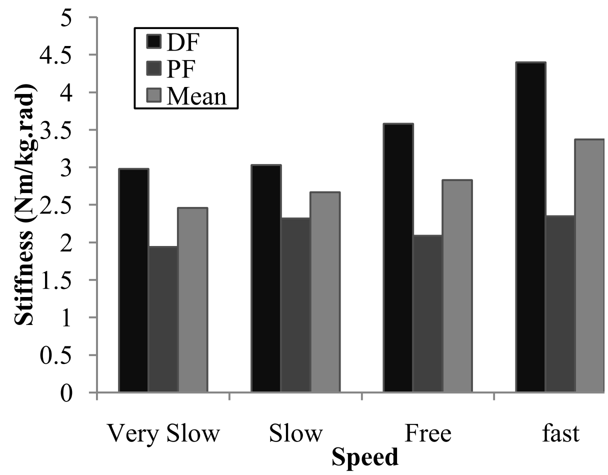

Figure 8. The characteristic stiffness of the ankle in the dorsi-flexion and plantar-flexion modes, and in the progression stage of the gait plotted against the gait speed.

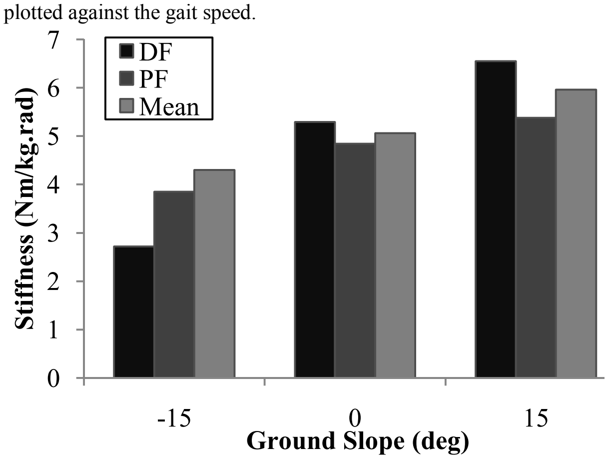

Figure 9. The characteristic stiffness of the ankle in the dorsi-flexion and plantar-flexion modes, and in the progression stage of the gait plotted against the ground slope.

It is clear from the results presented that the mechanical parameters of the ankle spring (stiffness, angle of zero moment, maximum travel and moment) change significantly from one study to the next and it is not possible to correlate these to individual subject parameters using the currently available literature. Further research over a wide range of subjects in a controlled setting is required in order to study those correlations and allow a spring to be chosen for a particular subject or range of subjects, ideally based on simple body measures such as height, leg length, and mass.

REFERENCES

[1] T. McGeer, "Passive Walking with Knees," *Proceedings., IEEE International Conference on Robotics and Automation*, pp. 1640-1645 vol.3, 13-18 May 1990.

[2] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot," *Proceedings. IEEE International Conference on Robotics and Automation*, vol.2, pp.1321-1326 vol.2, 16-20 May 1998.

[3] A.B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)," *IEEE/ASME Transactions on Mechatronics*, vol. 11, (no. 2), pp. 128-138, 2006.

[4] C.J. Walsh, D. Paluska, K. Pasch, W. Grand, A. Valiente, and H. Herr, "Development of a Lightweight, Underactuated Exoskeleton for Load-Carrying Augmentation," *ICRA. Proceedings IEEE International Conference on Robotics and Automation*, pp.3485-3491, 15-19 May 2006

[5] M.F. Eilenberg, H. Geyer, and Herr H., "Control of a Powered Ankle-Foot Prosthesis Based on Neuromuscular Model", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, (iss. 2), pp. 164-173, 2010.

[6] M. Palmer, *Sagittal Plane Characterization of Normal Human Ankle Function Across a Range of Walking Gait Speeds*. MS Thesis, Massachusetts Institute of Technology, Cambridge, 2002.

[7] R. B. Davis and P. A. DeLuca, "Gait Characterization via Dynamic Joint Stiffness", *Gait and Posture*, vol. 4, (iss. 3), pp. 224-231, 1996.

[8] R. Seymour, *Prosthetics and Orthotics Lower Limb and Spinal*. 3rd ed. MD: Lippincott Williams & Wilkins, 2002.

[9] D. P. Ferris, J. M. Czerniecki and B. Hannaford, "An Ankle-Foot Orthosis Powered by Artificial Pneumatic Muscles," *J. Appl. Biomech.* Vol. 21, (iss. 2), pp. 189–197, 2005.

[10] J. A. Blaya and H. Herr, "Adaptive Control of a Variable-Impedance Ankle-Foot Orthosis to Assist Drop-Foot Gait," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,*. Vol. 12, (iss. 1), pp. 24–31, 2004.

[11] P. L. Weiss, R. E. Kearney, and I. W. Hunter, "Position Dependence of Ankle Joint Dynamics – I. Passive Mechanics", *J. Biomechanics*, vol. 19, (no. 9), pp. 727-735, 1986.

[12] P. L. Weiss, R. E. Kearney, and I. W. Hunter, "Position Dependence of Ankle Joint Dynamics – I. Active Mechanics", *J. Biomechanics*, vol. 19, (no. 9), pp. 737-751, 1986.

[13] P. L. Weiss, I. W. Hunter, and R. E. Kearney, "Human Ankle Joint Stiffness Over the Full Range of Muscle Activation Levels", *J. Biomechanics*, vol. 21, (no. 7), pp. 539-544, 1988.

[14] G. B. Salsich and M. J. Mueller, "Effect of plantar flexor muscle stiffness on selected gait characteristics", *Gait and Posture*, vol. 11, pp. 207-216, 2000.

[15] C. Frigo and L. M. Jensen, "Moment-Angle Relationship at Lower Limb Joints during Human Walking at Different Velocities," *J. Electromyogr. Kinesiol.,* Vol. 6, (no. 3), pp. 177–190, 1996.

[16] J. Perry, Gait Analysis : Normal and Pathological Function, Thorofare, NJ: SLACK, 1992.

[17] E. Harman, K. Hoon, P. Frykman, and C. Pandorf, "The Effects of Backpack Weight on the Biomechanics of Load Carriage," Military Performance Division US Army Research Institute of Environmental Medicine, NATICK MA 2000.

[18] D.A. Winter, "Biomechanical Motor Patterns in Normal Walking," *Journal of Motor Behavior*, vol. 15, (no. 4), pp. 302-330, 1983.

[19] A. Cappozzo, "A General Computing Method for the Analysis of Human Locomotion," *J. Biomechanics*, vol. 8, pp. 307-320, 1975.

[20] J. Apkarian, S. Naumann, and B. Cairns, "A 3-Dimensional Kinematic and Dynamic-Model of the Lower-Limb," *Journal of Biomechanics*, vol. 22, (iss. 2), pp. 143-155, 1989.

[21] A. Pedotti, "A Study of Motor Coordination and Neuromuscular Activities in Human Locomotion," *Biological Cybernetics*, pp. 53-62, vol. 26, (iss. 1), p.57, 1977.

[22] M. Q. Liu, F. C. Anderson, M. H. Schwartz, and S. L. Delp, "Muscle Contributions to Support and Progression over a Range of Walking Speeds," *J. Biomechanics*, vol. 41, pp. 3243-3252, 2008.

[23] A. N. Lay, C. J. Hass, and R. J. Gregor, "The Effects of Sloped Surfaces on Locomotion: A Kinematic and Kinetic Analaysis," *J. Biomechanics*, vol. 39, pp. 1621-1628, 2006.

[24] R. Riener, M. Rabuffetti, and C. Frigo, "Stair Ascent and Descent at Different Inclinations," *Gait and Posture*, vol. 15, pp. 32-44, 2002.

[25] C. J. Nester, M. L. van der Linden, and P. Bowker, "Effect of Foot Orthoses on the Kinematics and Kinetics of Normal Walking Gait," *Gait and Posture*, vol. 17, pp. 180-187, 2003.

[26] G. Bovi, M. Rabuffetti, P. Mazzoleni, and M. Ferrarin, "A Multiple-Task Gait Analysis Approach: Kinematic, Kinetic and EMG Reference Data for Healthy Young and Adult Subjects," *Gait and Posture*, vol. 33, pp. 6-13, 2011.

[27] B. R. Umberger, "Effects of Suppressing Arm Swing on Kinematics, Kinetics, and Energetic of Human Walking," *J. Biomechanics*, vol. 41, pp. 2575-2580, 2008.

[28] M. P. Kadaba, H. K. Ramakrishnan, M. E. Wootten, J. Gainey, G. Gorton, and G. V. B. Cochran, "Repeatability of Kinematic, Kinetic, and Electromyographic Data in Normal Adult Gait," *J. Orthopaedic Research*, vol. 7, pp. 849-860, 1989.

[29] D. C. Kerrigan, M. K. Todd and U. Croce, "Gender Differences in Joint Biomechanics During Walking: Normative Study in Young Adults," *Am. J. Phys. Med. Rehabil.* Vol. 77, pp. 2–7, 1998.

[30] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. 3rd ed. NJ: John Wiley & Sons Inc., 2005.

[31] A. H. Hansen, D. S. Childress, S. C. Miff, S. A. Gard, K. P. Mesplay, "The Human Ankle During Walking: Implications for Design of Biomimetic Ankle Prostheses," *J. Biomechanics*, vol. 37, pp. 1467-1474, 2004.