AFRL-RH-WP-TR-2014-0016

DO MEN AND WOMEN WALK DIFFERENTLY? A REVIEW AND META-ANALYSIS OF SEX DIFFERENCE IN NON-PATHOLOGICAL GAIT KINEMATICS

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JANUARY 2014
Interim Report

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15 01 14	Interim	1 January 2013 – 15 January 2014

4. TITLE AND SUBTITLE
Do Men and Women Walk Differently? A Review and Meta-Analysis of Sex Difference in Non-Pathological Gait Kinematics

5a. CONTRACT NUMBER FA8650-12-D-6354

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62202F

6. AUTHOR(S)
Rebecca Frimenko
Cassie Whitehead
Dustin Bruening

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER H0FQ (5328B009)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
Air Force Research Laboratory
711th Human Performance Wing
Human Effectiveness Directorate
Human-Centered ISR Division
Human Signatures Branch
Wright-Patterson Air Force Base, OH 45433

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
711 HPW/RHXB

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RH-WP-TR-2014-0016

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
88ABW-2013-3853; Cleared 27 August 2013

14. ABSTRACT
The common perception that men and women walk differently has been supported by studies in psychology and human perception; however, in modern empirical kinematic studies, sex differences are surprisingly limited, contradictory, or equivocal. Interest in sex differences spans many fields, from psychology to medicine to surveillance. In this review, we assemble and analyze what is known about spatiotemporal and kinematic variables of female and male gait. Historical perspectives, which indicate that sex is identifiable from point-light walkers, are briefly canvassed to help guide identification of structural and kinematic differences. Both spatiotemporal and kinematic data from the past three decades are then presented and discussed. We further analyze the published data in order to identify how height-normalization may affect noted spatiotemporal differences between the sexes. Subsequently, gaps in published data, and the implication of such missing information on gait analysis, are identified. From the analysis performed herein, we suggest that the pooled literature indicates that gait speed decreases with age, and, furthermore, decreases more for women than men. The meta-analysis of spatiotemporal variables normalized to height implies that step length is height-dependent, and, when height-matched, women may walk at a slightly faster preferred speed than men. The compilation of kinematic data suggests that coronal plane pelvis and hip range of motion may be different between the sexes. However, further investigation is needed on nearly every body segment, with special attention to the torso and upper extremities, to explain and quantify or refute gait differences as identified through perception and psychology literature.

15. SUBJECT TERMS
Sex differences, gait, spatiotemporal, kinematics, point-light walkers

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
U	U	U	SAR	34	Dustin Bruening
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 SUMMARY

The common perception that men and women walk differently has been supported by studies in psychology and human perception; however, in modern empirical kinematic studies, sex differences are surprisingly limited, contradictory, or equivocal. Interest in sex differences spans many fields, from psychology to medicine to surveillance. In this review, we assemble and analyze what is known about spatiotemporal and kinematic variables of female and male gait. Historical perspectives, which indicate that sex is identifiable from point-light walkers, are briefly canvassed to help guide identification of structural and kinematic differences. Both spatiotemporal and kinematic data from the past three decades are then presented and discussed. We further analyze the published data in order to identify how height-normalization may affect noted spatiotemporal differences between the sexes. Subsequently, gaps in published data, and the implication of such missing information on gait analysis, are identified. From the analysis performed herein, we suggest that the pooled literature indicates that gait speed decreases with age, and, furthermore, decreases more for women than men. The meta-analysis of spatiotemporal variables normalized to height implies that step length is height-dependent, and, when height-matched, women may walk at a slightly faster preferred speed than men. The compilation of kinematic data suggests that coronal plane pelvis and hip range of motion may be different between the sexes. However, further investigation is needed on nearly every body segment, with special attention to the torso and upper extremities, to explain and quantify or refute gait differences as identified through perception and psychology literature.

2.0 INTRODUCTION

There is a common perception that men and women walk differently. Psychologists, for example, have consistently noted that observers can identify the sex of a person from limited gait information [1, 2]. Yet, as this review will demonstrate, controlled studies quantifying the differences between sexes have been surprisingly limited, contradictory, or equivocal. There may also be important distinctions between sex differences (inherent biological characteristics) and gender differences (learned socio-cultural attributes) that have not been fully delineated. This review will assemble and synthesize published comparisons of female and male subjects in order to understand gait differences between the sexes.

Understanding sex differences during gait has immediate impact to the fields of medicine and clinical gait analysis. Many injuries and pathologies have a strong sex component. For example, non-contact anterior cruciate ligament tears occur more frequently in females than males [3, 4]. While this injury is a consequence of running and cutting motions, underlying musculoskeletal differences between the sexes have been implicated as a cause of the injurious motions. Because these are inherent structural differences, each will influence normal gait as well [5]. Wearing high-heels has been shown to change bone and ligament properties [6], thus supplying a cultural force resulting in further structural differences. It is evident that certain diseases affect one sex more often than the other (e.g. osteoarthritis [7, 8], Parkinson's disease [9, 10], and diabetes [11, 12]), and these diseases often have implications to the kinematics of gait. Thus, rates of disease incidence may also prompt separation of gait analysis between sexes. While research studies generally present sample demographics separately for female and male subjects, gait data are commonly pooled during analysis. As a result, diagnostic and rehabilitation guides do not differentiate between sexes, though there may be situational prompts to do so. One goal of this review is to help identify areas where normative data may warrant separation for female and male subjects.

Beyond direct clinical applications, other disciplines and industries have a vested interest in understanding the implications of sex on gait. Psychologists are often interested in differentiating between biological and socio-cultural factors influencing gender development. Sex identification through the use of gait signatures (i.e. biometrics) may aid automated surveillance for threat detection, tracking, and consumer statistics. Engineers and artists within the entertainment industry may use this synthesis of gait parameters to help design more biofidelic avatars and computer-generated special effects. In biomedical engineering applications, sex-specific gait characteristics may inform the design of joint replacements, prosthetics, and robotics exoskeletons for walking rehabilitation. Neurology and motor control experts may also be interested in possible differences in neuromuscular control strategies between sexes.

The purpose of this review, therefore, is to integrate, from all relevant disciplines, what is known about the influence of sex on the kinematics of non-pathological gait. We first examine sex differences in gait through a historical perspective to describe early motivation and initial perceptions. Then results and discussion are presented for modern empirical studies of spatiotemporal variables and kinematics of individual body segments. In presenting the amalgamation of research, this review will establish trends in kinematic data, identify gaps in the current body of knowledge, and suggest areas for future research.

3.0 EARLY STUDIES AND HUMAN PERCEPTION

The earliest published modern gait studies with a specific focus on sex differences appear in the 1950s, 60s and 70s. In 1966 and 1970 Murray et al. published two separate studies [13, 14] describing walking kinematics of males and females, respectively, comparing the two groups in the latter study. These authors found that women walked with smaller excursions in most joints than men. This included reduced sagittal plane motion of the hips resulting in shorter normalized step lengths, corroborating a finding earlier postulated by Booyens et al. [15]. However, the observation which received the most critical attention was that of increased coronal plane pelvis excursions in women, with an accompanying decrease in mediolateral torso and head movement. Murray and colleagues suggested that necessary movement of the center of mass from side to side could be accomplished by either moving the pelvis or the torso, the choice of which was likely an "attitudinal," or socio-cultural characteristic that differed between the sexes.

Murray's findings influenced several subsequent studies on the ability of human observers to recognize sex during gait. During these studies, psychologists attached lights or reflective tape to body segments and recorded motion in a dark room. Subjects then watched videos of these point-light walkers (PLW) and were asked identification questions based solely upon the motion of the lights, without any knowledge or cues of the original walker. Kozlowski and Cutting [2] first used the PLW technique to show that subjects could determine the sex of the walker with values significantly greater than chance. Subsequently, PLW studies examined the effects of walking speed, variations in arm swing, and darkening various body segments on sex recognition [1, 2, 16-18]. Altering walking speed, either physically or virtually, decreased the percent of PLWs correctly identified with the right sex. Similarly, removing points of light from a walker decreased identification; however, viewers correctly identified sex significantly more often when only upper-body segments were illuminated than when only lower-body lights were shown [2].

Prompted by these results, a series of studies examined cues of sex identification, seeking a single variable to explain human observations: an invariant. Cutting et al. settled on what the authors termed "Center of Moment" (CoM) [18], the ratio of shoulder width to the sum of shoulder and hip width. This terminology was chosen to suggest a dynamic construct, explaining that it might represent a point about which all transverse plane rotation occurs. Biomechanically, this is an overly simplistic view of the human body, and the CoM theory remains primarily a structure-based invariant. Hypothesizing that Murray's [19] observation of increased mediolateral torso excursion was a defining characteristic, Mather and Murdoch [20] investigated whether this dynamic cue was more telling than the structurally-based CoM. By synthetically varying the relative widths of shoulder and hips to develop a female torso, male torso, or androgynous torso, while at the same time varying torso and pelvis excursions to develop the female, male, or androgynous lateral sway, these authors concluded that lateral torso movement dominated as the defining invariant for sex identification during gait.

The debate whether structural or dynamic cues dominate observer sex recognition was later examined in computer vision literature and further examined in psychology using modern simulation techniques. Troje et al. decomposed analysis of PLW trajectories using principal component analysis, finding that the dynamic signal content contributed more to correct sex classification than did the static postural (structural) content. On the other hand, studies that used silhouettes as stimuli instead of PLWs found reversed results [21, 22], suggesting that the specific cues that are used for sex recognition are likely to be heavily dependent upon the type of stimuli that is available. In both cases, however, gaze analysis indicated primary focus on the pelvis and torso areas [21, 23], consistent with early attempts at describing an invariant.

Thus, over several decades and with myriad techniques, the fields of psychology and perception indicate a striking difference in female and male gait that can be discerned by human observers. While the review of this body of literature has been cursory in its details, it illustrates the lessons learned from examining how we perceive sex differences. These studies have established that there are apparent, defining movement characteristics differentiating males from females with these movement cues primarily residing in the pelvis and torso. In beginning to examine motion from an empirical standpoint, we would expect to see significant, quantifiable differences between these areas.

4.0 METHODS

Potentially relevant articles across the general fields of medicine, engineering, and psychology were identified with an electronic search of PubMed, Web of Science, PsychInfo, and Google Scholar. Additional papers were identified from cited references. Papers were excluded from this review if they did not contain information about non-pathological subjects, if the study did not analyze kinematics of walking, or if the study only examined a single sex without a means of comparing to the other sex.

After reviewing all articles, we noted that there were a sufficient number of studies reporting spatiotemporal metrics (preferred speed, cadence, and step length) separately by sex to look for larger trends through a meta-analysis. We analyzed spatiotemporal data from reviewed articles in three ways: within-study comparison of sex differences when not already performed and reported (Method 1), across-study sex differences within age bins (meta-analysis Method 2), and across-study sex differences with height as a covariate (meta-analysis Method 3). Significance level for all analysis modes was set at $p < 0.05$.

For studies that reported separate metrics by sex but fell short of analysis, we calculated two-tailed, two-sample t-tests using the published means, standard deviations, and subject numbers (Method 1).

For Method 2, four distinct age bins were used to investigate sex differences in age. These bins (20 - 40, 43 - 58, 62 - 75, and 77 - 95 years old) were chosen where natural breaking points occurred in the data. If an individual study reported multiple age groups within our chosen bins, standard deviations were pooled and a single, weighted mean was calculated. Preliminary analysis and graphing did not indicate issues which prevented pooling of standard deviations across studies, sexes, or bins. Across study weighted means and pooled standard deviations were then determined for each combination of age bin and sex, and two-tailed t-tests were used to test for sex differences within and across each age bin. Though two-tailed t-tests were used to perform this analysis, combining data from different studies can be problematic, and p-values should be interpreted cautiously.

For studies that also listed height by sex, this variable was examined as a possible explanation for spatiotemporal differences between sexes (Method 3). We analyzed each spatiotemporal metric using height as both a covariant as well as a normalization factor, with each study treated as a subject in analyses. As above, p-values should be treated cautiously and results used only as a guide for future work.

5.0 SPATIOTEMPORAL METRICS

Of all measurable gait parameters, spatiotemporal metrics are reported and described most often. These variables are easily obtainable and have been found to correlate with pathologies, injury outcome, and rehabilitation [24, 25]. This section will summarize the effects of sex on these variables by reporting published observations as well as reanalyzing data through the three methods mentioned above.

5.1 Gait Speed

Bohannon and Andrews [26] authored a meta-analysis of preferred walking speeds, compiling data on more than 23,000 subjects across 41 studies. Of these, 21 included information about both females and males [27-47]. We found an additional 26 studies which listed gait speed by sex [5, 8, 19, 24, 48-69], and all 47 articles were examined for intra-study significance (Method 1). Gait speed was found to be significantly different between the sexes in less than 25% of studies examining 20 - 59 year olds, while more than 40% of the studies which recorded speed on 60 - 99 year olds were significantly different (**Table** 1). Because weighted means accounted for thousands of subjects, our meta-analysis (Method 2) resulted in significant differences between sexes at each of the four age bins (Figure 1A), with males being faster than females. Furthermore, we examined the drop in mean gait speed as age increases, and found a significantly increased gap between females and males at the oldest and youngest age bins. This analysis confirms what is noted in previous studies (e.g. Senden et al. 2012 [70]) that female gait speed decreases proportionally more with age than that of men.

Table 1: Distribution of Studies Reporting Significantly Different, Self-Selected, Preferred, Over-Ground Gait Speed by Age Decade

Normative values have been previously published by Bohannon et al. [26]. Every study but one [69] which reported a significant difference in gait speed found females to be slower than males.

Age Group (Years Old)	Total Number Of Studies	Number Of Significantly Different Studies (% Of Age Group)
20 - 29	13	3 (23%)
30 - 39	7	1 (14%)
40 - 49	8	1 (13%)
50 - 59	6	1 (17%)
60 - 69	16	7 (44%)
70 - 79	27	14 (52%)
80 - 99	17	10 (5 %)

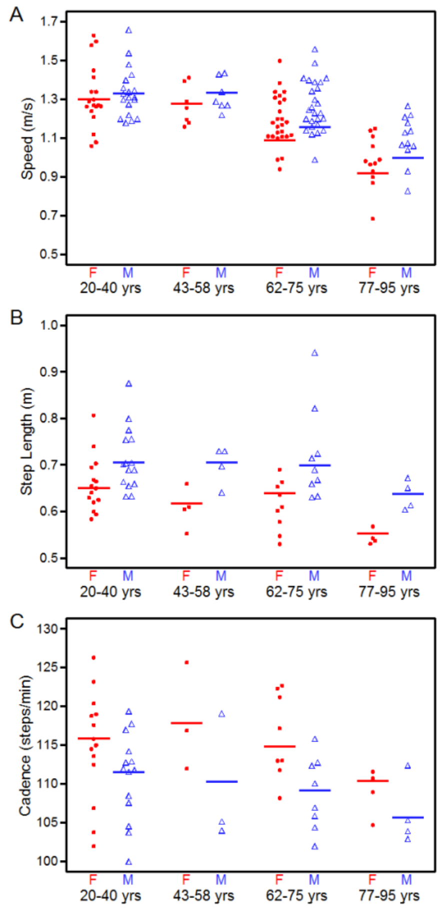

Figure 1: Plots of Mean Spatiotemporal Variables by Sex and Age

Data taken from studies which reported means for preferred, self-selected, over-ground speed only. Multiple age groups in the same study/bin were pooled. Colored horizontal line segments represent averages of study means. Significant differences (p<0.05) were found for every comparison of female and male values, due in part to having thousands of subjects in each comparison so that relatively small differences (e.g. gait speed at 20 - 40 years old) were significant. A.) Male speed was greater in every age group (178 studies). Females demonstrated a greater decrease in gait speed as age increased. B.) Male step length was greater in every age group (86 studies). Females exhibited a greater decrease in step length as age increased. C.) Female cadence was greater in every age group (80 studies).

5.2 Cadence and Step Length

Twenty-four studies comprising 100 age groups published step lengths for each sex (Table 2). Of these 100 age groups, 74 age groups, across 21 studies, were found to have significant differences between sexes (Method 1). All 74 age groups reported that males had a significantly greater step length than females. This was also confirmed in our meta-analysis (Method 2), which showed significant differences at each age bin (Table 2, Figure 1B).

Table 2: Cadence and Step Length for Various Studies

Mean ± standard deviation. Significant differences between the sexes are reported as (*) for step length and (#) for cadence.

Study	Pace^{Y}	T or OG$^{\beta}$	No. Subjects		Age (years)		Step Length (cm)		Cadence (step/min)	
			Female	Male	Female	Male	Female	Male	Female	Male
Al-Obaidi et al. [27]	Slow SS	OG	15	15	23 ± 2	26±3	53 ± 7	57± 6	89 ± 10	85 ± 11
	Normal SS*						63 ± 6	70 ± 7	104 ± 7	104 ± 9
	Fast SS*						71 ± 7	83 ± 7	135± 14	131±16
Alton et al. [48]	Normal SS	OG	8	9	24 ± 6	28±5	62 ± 6	66 ± 7	119 ± 5	117 ± 6
		T	8	9			65 ± 7	69 ± 8	123 ± 3	122 ± 4
Bessou et al. [92]	Normal SS*	OG	25	25	39 ± 11	40±12	74 ± 6	78 ± 6		
Boyer et al. [8]	Normal SS*	OG	21	21	62 ± 5	61±5			118	105
Callisaya et al. [35]	Normal SS*	OG	22	15	60 - 64		61 ± 6	69 ± 7	115 ± 9	110±11
	Normal SS*#		21	28	65 - 69		59 ± 6	68 ± 7	118 ± 7	107 ± 7
	Normal SS#		15	27	70 - 74		61 ± 7	65 ± 7	120 ±11	106 ±7
	Normal SS*#		27	26	75 - 79		55 ± 7	61 ± 9	113 ± 8	106±10
	Normal SS*		17	24	80 - 86		50 ± 8	60 ± 8	107 ±12	105 ±8
Chao et al. [93]	Normal SS*	OG	20	21	19 - 32		60 ± 7	69 ± 9	102 ±10	100±16
	Normal SS*#		37	32	32 - 85		61 ± 8	73 ± 8	112 ±10	104±10
Chiu & Wang [19]	IS	T	15	15	24 ± 2	25±2			119± 16	115±13
Cho et al. [50]	Normal SS*	OG	47	51	23 ± 5	24 ± 3	58 ± 6	63 ± 5	113 ± 7	112 ± 6
Chockalingam et al. [51]	Normal SS	OG	6	8	24 ± 4	23 ± 3			115 ± 6	114 ± 6
		T							102 ± 6	96 ± 6
Chui and Lusardi [52]	Normal SS*	OG	15	4	70-79		65 ± 8	82±17	122± 13	112±22
	Normal SS*#		51	26	80-89		56 ± 5	68 ± 6	111 ± 5	114 ± 6
	Normal SS		17	5	90-99		46 ± 7	62± 18	103 ± 9	105 ± 8
	Fast SS*		15	4	70-79		70 ± 10	93± 14	143± 13	140±32
	Fast SS*		51	26	80-89		62 ± 5	77 ± 6	138 ± 7	137 ± 9
	Fast SS		17	5	90-99		50 ± 8	71± 23	125± 12	130±17
Chung et al.[54]	Normal SS*#	OG	11	9	29 ± 6	32 ± 6	63 ± 3	66 ± 3	115 ± 8	108 ± 4
Crosbie & Vachalathiti [56]	Normal SS*	OG	58	50	45±19	46±19	66 ± 1	73 ± 1		
	Fast SS*						75 ± 2	87 ± 2		
Crosbie et al. [55]	Normal SS*#	OG	35	30	< = 50	< = 50	69 ± 6	75± 14	117±11	110±10
	Normal SS*		23	20	>50	>50	62 ± 9	69 ± 7	117 ± 7	112±10
	Fast SS *#		35	30	< = 50	< = 50	81 ± 10	91± 17	143± 15	133±13
	Fast SS *#		23	20	>50	>50	67 ± 11	80± 11	138± 10	131±12
Eke-Okoro & Sandlund [57]	Normal SS*#	OG	22	64	20 - 70		78 ± 7	83 ± 8	121± 11	116 ± 8
Finley & Cody [58]	Normal SS*#	OG	572	534			63 ± 7	74 ± 9	116± 12	110±10
Forczek & Staszkiewicz [59]	Normal SS#	OG	27	27	18 - 25				123 ± 6	118 ± 5
Hageman & Blanke [94] and Blanke & Hageman [95]	Normal SS*	OG	13	12	24 ± 4	25 ± 4	81 ± 5	88 ± 6		
	Normal SS*		13	12	67 ± 8	64 ± 6	66 ± 7	94 ±12		

Hollman et al. [69]	Normal SS*#	OG	33	27	70 - 74		61 ± 9	69 ± 8	113 ±20	102 ± 8
	Normal SS*#		77	30	75 - 79		59 ± 7	68 ± 7	114 ±13	106±10
	Normal SS*#		43	37	80 - 84		55 ± 7	65 ± 8	110 ± 9	103 ± 8
	Normal SS*		33	14	85+		54 ± 9	59 ±10	108 ±10	102±11
Kadaba et al. [61]	Normal SS	OG	12	28	18-45		65 ± 5	71 ± 7	115 ± 9	112 ± 9
Kerrigan et al. [62]	Normal SS*#	OG	49	50	29 ± 5	28 ± 5	67 ± 5	69 ± 6	120± 10	113 ± 9
Ko et al.	Normal SS*#	OG	162	174	69 ± 9	73±10	69 ± 5	72 ± 5	113 ± 1	110 ± 1
Laufer [24]	Normal SS*	OG	15	15	24 ± 2		70 ± 5	75 ± 5	123 ± 9	118±10
			20	20	78 ± 6		54 ± 10	61 ± 9	104± 10	103±13
Mazza et al. [64]	Normal SS	OG	20	20	23 ± 3	23 ± 3			114 ± 1	107 ± 1
	Fast SS								131 ± 1	125 ± 1
Mazza et al.[65]	Normal SS	OG	15	15	9 ± 1	9 ± 1			103± 14	108 ± 8
Oberg et al. [40]	Slow SS*#	OG	12	12	10-14		47 ± 3	52 ± 3	89 ± 13	101±11
	Slow SS		15	15	15-19		52 ± 4	54 ± 7	101± 13	93 ± 17
	Slow SS		15	15	20-29		52 ± 7	53 ± 3	95 ± 12	93 ± 8
	Slow SS		15	15	30-39		52 ± 5	55 ± 5	98 ± 12	93 ± 15
	Slow SS*		15	15	40-49		49 ± 5	56 ± 3	97 ± 14	98 ± 12
	Slow SS*		15	15	50-59		47 ± 3	55 ± 7	92 ± 17	92 ± 9
	Slow SS*		15	15	60-69		48 ± 5	56 ± 4	90 ± 17	93 ± 11
	Slow SS*		15	14	70-79		47 ± 4	53 ± 5	92 ± 7	89 ± 8
	Normal SS*#		12	12	10-14		54 ± 3	62 ± 4	118± 10	128±11
	Normal SS*		15	15	15-19		59 ± 4	66 ± 5	125± 11	121±12
	Normal SS		15	15	20-29		59 ± 6	62 ± 4	125 ± 9	119 ± 8
	Normal SS*#		15	15	30-39		60 ± 5	65 ± 5	128± 10	120 ± 8
	Normal SS*#		15	15	40-49		57 ± 4	65 ± 4	130± 10	121 ± 7
	Normal SS*		15	15	50-59		54 ± 3	64 ± 6	122 ± 8	118±11
	Normal SS*		15	15	60-69		55 ± 4	65 ± 4	124± 11	117 ± 8
	Normal SS*#		15	14	70-79		54 ± 4	62 ± 5	122 ± 8	115 ± 8
	Fast SS*		12	12	10-14		63 ± 5	69 ± 8	145± 11	151±17
	Fast SS*		15	15	15-19		68 ± 4	79 ± 6	152± 16	145±14
	Fast SS*#		15	15	20-29		67 ± 6	71 ± 6	154± 15	140±10
	Fast SS*#		15	15	30-39		69 ± 7	76 ± 8	155± 14	143±14
	Fast SS*#		15	15	40-49		65 ± 4	74 ± 4	157± 15	143±13
	Fast SS*		15	15	50-59		60 ± 5	72 ± 6	149± 14	140±19
	Fast SS*#		15	15	60-69		63 ± 6	74 ± 5	152± 14	139±11
	Fast SS*		15	14	70-79		60 ± 4	72 ± 7	144± 13	136±14
Richard et al. [96]	Normal SS*#	OG	6	8	23 ± 3	27 ± 4	68 ± 4	80 ± 7	115 ± 8	105 ±5
	Normal SS*#		9	11	35 ± 3	35 ± 3	66 ± 5	80 ± 6	113 ± 6	104 ±11
	Normal SS*		14	5	46 ± 3	43 ± 4	62 ± 7	75 ± 2	117 ± 9	110 ± 7
	Normal SS*#		6	7	55 ± 3	57 ± 1	57 ± 6	66 ± 7	116 ± 7	102 ±10
	Normal SS*		6	7	74 ± 6	66 ± 3	53 ± 8	66 ± 6	112 ±10	104 ± 3
Sato & Ishizu [66][A]	Morning SS*	OG	57	10	~15-24		65 ± 6	78 ± 6	128± 12	120 ± 7
	Afternoon SS*#		103	4			66 ± 5	75 ± 8	126 ± 9	116 ± 8
	Evening SS#		46	9			64 ± 5	71 ± 9	122± 12	111 ± 6
	Morning SS*#		29	19	~25-34		69 ± 5	78 ± 5	137± 11	128 ± 7
	Afternoon SS*		15	3			64 ± 5	74 ± 5	129± 14	116±17
	Evening SS*#		6	6			63 ± 2	74 ± 6	124 ± 8	117 ± 6
	Morning SS*#		10	29	~35-44		64 ± 3	76 ± 5	136± 13	123 ± 8
	Afternoon SS*		5	8			64 ± 6	72 ± 7	125 ± 9	119 ± 7

	Evening SS		2	2			62 ± 3	67 ± 6	120 ± 5	115 ± 4
	Morning SS*		4	12	~45+		58 ± 4	71 ± 7	122± 17	115±11
	Afternoon SS*#		11	9			59 ± 5	69 ± 6	122± 10	113 ± 5
	Evening SS*		4	6			55 ± 2	70± 10	112 ± 6	114 ± 7
Sekiya & Nagaskai 1998 [68]	Slowest SS	OG	17	8	23 ± 4	22 ± 4	58 ± 5	55± 11	77 ± 8	83 ± 9
	Slow SS						65 ± 6	65 ± 6	96 ± 8	97 ± 6
	Normal SS						70 ± 6	66 ± 5	107 ± 8	109 ± 8
	Fast SS						76 ± 6	74 ± 4	121 ± 9	116 ± 7
	Fastest SS						85 ± 6	88 ± 8	135± 12	133 ± 8
Smith et al. [67]	Normal SS*#	OG	30	30	29 ± 6	30 ± 6	64 ± 5	70 ± 7	119 ± 9	112±10
	Normal SS*#		30	30	72 ± 5	72 ± 5	58 ± 5	63 ± 8	121± 10	113 ± 7
Waters et al. [97]	Slow SS#	OG	27	34	9 ± 2	9 ± 2	54 ± 7	53 ±12	99 ± 9.3	105 ± 9
	Slow SS#		28	25	16 ± 2	16 ± 2	59 ± 13	61 ±17	95 ± 6	89 ± 0
	Slow SS		34	39	40 ±14	39 ±12	45 ± 23	52 ±24	68 ± 20	76 ± 17
	Slow SS		47	26	69 ± 5	67 ± 5	54 ± 13	58 ±19	85 ± 14	79 ± 13
	Normal SS		27	34	9 ± 2	9 ± 2	57 ± 7	59 ± 7	119 ± 9	120 ± 8
	Normal SS*#		28	25	16 ± 2	16 ± 2	68 ± 7	73 ± 8	107 ± 7	100 ± 8
	Normal SS*#		34	39	40 ±14	39 ±12	66 ± 7	76 ± 7	118 ±10	108 ± 9
	Normal SS*#		47	26	69 ± 5	67± 5	64 ± 7	73 ± 7	113 ± 9	106±10
	Fast SS		27	34	9 ± 2	9 ± 2	63 ± 15	65 ± 9	135 ± 7	136 ± 9
	Fast SS#		28	25	16 ± 2	16 ± 2	81 ± 19	85 ± 9	124 ±15	116 ± 9
	Fast SS*#		34	39	40 ±14	39 ±12	62 ± 27	84 ±21	137 ±11	125±12
	Fast SS*#		47	26	69 ± 5	67 ± 5	66 ± 15	82 ± 7	124 ±10	119 ± 8

Ɏ SS: self-selected speed during testing. IS: instructed speed during testing. Sato and Ishizu (1990) is delineated by time of day rather than gait speed.
ᴷT: gait conducted on the treadmill. OG: gait conducted over-ground.

Cadence values were reported in 102 age groups across 26 studies. Of these 102 age groups, 45 (44%) indicated differences between the sexes (Method 1, **Table 2**). In 41 of the 45 studies which reported a significant difference, females demonstrated significantly higher cadence values than men. In our meta-analysis (Method 2), females were again shown to have a significantly faster cadence than males at each age bin (**Figure 1C**).

Both step length and cadence were also examined across age bins for relative decrease of each metric between sexes as age increases (Method 2, **Figure 1**). There was a significant difference in separation between step lengths taken by men and women at young (20-40 years) versus old (77-95 years) ages, while no differences were noted in cadence. While walking speed decreases in elderly females and males, and this is a result of decreases in both cadence and step length, our meta-analysis suggested that the greater, relative decrease in speed by elderly women was more a result of relatively smaller steps taken by elderly women than a relative drop in cadence.

5.3 Normalized Metrics

Just six studies investigated normalized gait speed, step length, or cadence. A variety of normalization variables were used: height [31, 55, 62, 70], leg length [52], and square root of leg length [54]. Female/male differences were sporadic and mixed, and we could not generalize any trends from the individual studies. However, we sought additional insight by performing a meta-analysis using height as a covariate and normalization factor (Method 3, **Figure 2**).

Using height as a covariate, we showed no significant differences between sexes in gait speed or step length, while, conversely, the difference in cadence was magnified. In particular, in the cross-plot of step length with height, the regression lines for female and male subjects are nearly identical. Step length had a height effect, not a sex effect, indicating that, though women are shorter than men, height-matched subjects of opposite sexes likely have similar step lengths (**Figure 2C**). Unsurprisingly, when the effect of height on gait speed is examined, females - owing to equal step length and higher cadence - may be slightly faster than height-matched males (**Figure 2A**).

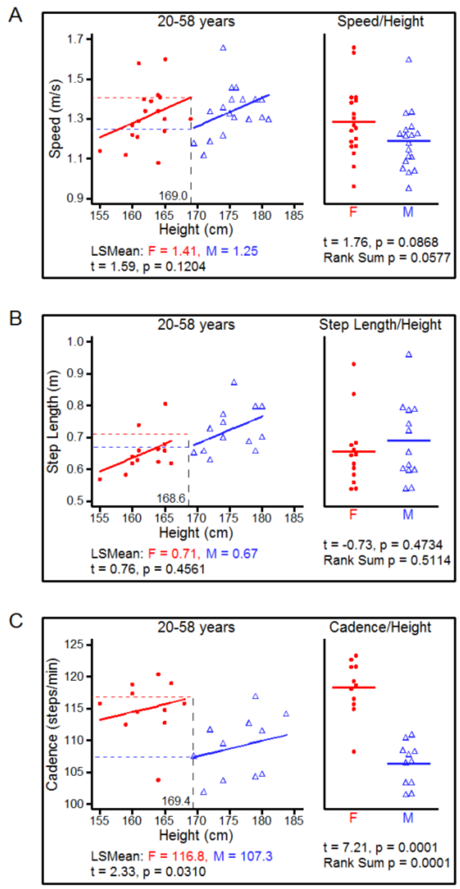

Figure 2: Plots of Height and Spatiotemporal Variables

Only reviewed articles which included means of height along with at least one of gait speed, step length, or cadence at preferred, self-selected, over-ground speed were included. A.) Gait speed with height as a covariate (18 studies). For height-matched subjects, females are faster than males. B.) Step length with height as a covariate (13 studies). For height-matched subjects, there is no step length difference for females and males. C.) Cadence with height as a covariate (11 studies). For height-matched subjects, females have a higher though insignificant cadence than males.

5.4 Gait Phases and Step Width

Stance and double support phases, evaluated as percent of the gait cycle, were not found to be different between the sexes in four studies [24, 50, 51, 61] reporting these variables within three age groups: 20-30 years old, 70-80 years old, and 18-45 years old. Similarly, Alton et al. [48] found no difference in 20-30 year olds in the absolute time spent in stance and swing phase. On the other hand, Chui and Lusardi [52] reported that 80-89 year old females exhibited a significantly greater percent of the gait cycle in both stance and double support phases than males at preferred and fast self-selected speeds. Hollman et al. [69] found that females aged 80 - 84 years old spent less time in the swing phase and more time in double support than males but no differences were found in stance phase as a percent of the gait cycle. The combination of these limited studies suggested that there is likely a strong age affect if any differences in gait phases exist between females and males.

Step width was recorded in three studies [50, 62, 69]. Though both Cho et al. and Holloman et al. found evidence of a significant difference between men and women, with men taking wider steps, this data is too sparse to generalize. If a difference in step width does exist, structural factors (e.g. pelvic width, quadriceps angle [Q-angle], or overall body size) may be analyzed as explanatory variables.

5.5 Spatiotemporal Discussion

This review indicated a significant difference between sexes for gait speed, step length, and cadence, with differences becoming more pronounced with increasing age. Though results from individual studies were equivocal and, at times, conflicting, our meta-analysis illuminated trends observed when viewing the body of literature as a whole. Furthermore, while spatiotemporal variables and leg length or height seemed intuitively correlated, many studies neither reported these measures nor normalized gait speed or step length. Using a study's mean height as a covariate, we evaluated the effect of sex on step length. The meta-analysis suggested that men walked faster than women entirely because they were taller. Height was used in this analysis because it was published more frequently, yet leg length may be more appropriate as a normalization variable, especially when considering elderly subjects. We should note, however, that there are real limitations in any meta-analysis, and the p-values presented here should be interpreted with caution and not as though from a controlled study. As with all meta-analyses, these results require support of many individual studies.

Large variations in spatiotemporal metrics were observed between referenced studies (e.g. Bohannon et al. 2011 [26]). Imprecise equipment, varying subject conditions (time of testing during the day, rushed or hurried testing, etc.), analyzing multiple age groups together, and small datasets will influence significance of data. Well-controlled, repeatable laboratory conditions with large datasets are needed to establish normative values. Similarly, factors such as lifestyle and culture likely affect preferred walking speed, step length and cadence [1]. For example, Al-Obaidi et al. [27] examined values of both Kuwaiti subjects with matched Swedish subjects. Significant differences were intermittently noted for each sex between the two ethnicities and cultures. Though location and language are obvious barriers to international studies, additional study is needed to evaluate the effect of culture on spatiotemporal variables.

Additionally, three reviewed studies were recorded with subjects moving in an urban setting while unaware they were being observed. Finley and Cody [58], who examined pedestrians in four locations around Philadelphia, PA, USA, observed a difference in gait speed, step length, and cadence. While Eke-Okoro and Sandlund [57] found no difference in gait speed, this study found both cadence and step length to be different. Similarly, Sato and Ishizu [66] reported significantly different step length between the sexes at nearly every age group and time of day; gait speed and cadence were sporadically observed as significantly different. An important observation by these authors is that females, particularly young females, tended to walk in groups. These authors began to examine group dynamics, suggesting that gait speed, step length, and cadence are all significantly different under group-walking conditions.

6.0 KINEMATICS

Kinematic comparisons between sexes have primarily been analyzed using discrete joint angle metrics. Range of motion (ROM) has been the most frequently reported variable in the clinical literature, with some additional reporting of mean, maximum, or minimum values during a gait cycle. These latter variables are often more related to structure than to motion, and care should be taken to separate structural and movement effects. Also, these metrics may be more susceptible to marker placement errors and differences in segment reference frame definitions, resulting in greater variability across studies.

6.1 Pelvis

A single significant difference was found among seven studies reporting sagittal plane pelvic ROM [50, 51, 53, 55, 56, 61, 67], with Crosbie et al. describing a difference in the younger group at normal, self-selected speed (**Table 3**) [56]. Cho et al. reported a significant difference in the mean value across the gait cycle, with the female pelvis tilted more anteriorly [50]. This difference, which has been noted in static descriptions of anatomy (e.g. [71-73]), is a manifestation of structural, rather than kinematics, differences.

Pelvic ROM in the coronal plane has not had a consistent label in the clinical literature, with the seven studies reporting this motion alternately labeling it as obliquity, lateral tilt, list, or lateral flexion [50, 51, 53, 55, 56, 61, 67]. In four of these seven studies, females exhibited significantly greater ROM than males (**Table 3**). Crosbie was the lone author, with two studies, to find greater male ROM than female [55, 56]. In both Crobie's and Smith's [67] studies, significant differences were found in elderly subjects, but not younger subjects. This suggests a possible age/sex interaction, although the direction of the interaction was reversed between the two authors. Two studies conducted trials on a treadmill. Though Chumanov et al. [53] found the same trend of coronal plane difference as the over-ground studies, values reported by Chockalingam et al. [51] only bordered on significance ($.05<p<.08$).

Of the six studies reporting transverse plane pelvic ROM, three found no significant difference between the sexes [50, 61, 67] **(Table 3**). Of the remaining three studies, females demonstrated a significantly greater transverse plane pelvic ROM in the younger group of both studies by Crosbie et al. [55, 56] and the treadmill condition of Chockalingam et al. [51]. Normalized step lengths were reported for the second study by Crosbie et al. and were not found to be significantly different between males and females [56]. This suggests that the kinematic difference cannot be explained by coupling between transverse plane pelvis rotation and effective step length [74].

Table 3: Pelvic ROM

** indicates difference between the sexes (p < .05) and is given on the female value for the female/male pair. 'D:' Indicates a derived ROM from published maximum and minimum values. Statistical significance in this case is based upon significance of either maximum or minimum published values. ¤ indicates that significance was not given and was not able to be derived. ± indicates a standard deviation and () indicates a SEM value. ᵡTreadmill (T) or Overground (OG). 'SS' indicates a self-selected gait speed.*

					Range of Motion (deg)					
					Sagittal Plane		Coronal Plane		Transverse Plane	
Study	Speed	Age (years)	No. Subjects	T or OGᵡ	Female	Male	Female	Male	Female	Male
Cho et al. 2004	Normal SS	20-29	98	OG	≈1¤	≈1	D: 10*	D: 8	D: 6	D: 8
Chockalingam et al. 2012	Normal SS	20 - 29	14	OG	D: 1	D: 2	D: 14*	D: 7	D: 8	D: 7
				T	D: 1	D: 2	D: 8	D: 5	D: 3*	D: 1
Chumanov et al. 2008	1.2 m/s	20 - 29	34	T			9 ± 2*	7±2		
	1.5 m/s						10 ± 2*	7±2		
	1.8 m/s						10 ± 2*	8±2		
Crosbie and Vachalathiti 1997	Normal SS	40 - 59	108	OG	5 (0)	5 (0)	7 (0)	7 (0)	5 (0)*	4 (0)
	Fast SS				6 (0)	7 (0)	9 (1)*	11 (1)	6 (0)	5 (0)
Crosbie et al. 1997	Normal SS	<=50	85	OG	3 ± 1*	5 ± 2	7 ± 3	7 ± 3	5 ± 3*	4 ± 2
		>50	43		4 ± 2	3 ± 2	5 ± 2*	7 ± 2	4 ± 2	3 ± 2
	Fast SS	<=50	85		5 ± 2	6 ± 2	10 ± 4	11 ±4	7 ± 3	6 ± 3
		>50	43		5 ± 2	5 ± 2	7 ± 3*	10 ± 5	5 ± 3	4 ± 2
Kadaba et al. 1990	Normal SS	18 - 45	40	OG	Not significant		Not significant		Not significant	
Smith et al. 2002	Normal SS	20 - 40	30	OG	2 ± 1	2 ± 1	11 ± 3	10 ± 3	12 ± 4	12 ± 4
		60 - 89	30		2 ± 1	2 ± 1	8 ± 3*	5 ± 2	11 ± 4	9 ± 4

6.2 Hip

Hip ROM was most often reported in the sagittal plane (**Table 4**). Just one [75] of nine studies [5, 48, 50, 55, 56, 61, 62, 76] which reported ROM values found significant differences, with male ROM greater than female ROM. When examining left- and right-side differences, Oberg et al. concluded that a side difference may exist in females at normal and fast walking speeds, while Cho et al. did not find any significant side differences. Though ROM was not reported, Boyer et al. [8] noted significantly greater peak hip extension in females at toe-off. Structurally, Cho et al. [50] found a difference in the mean hip angle across the gait cycle, likely due to the previously mentioned structural difference in female and male pelvic tilt.

In the coronal plane, all four [5, 53, 61, 75] of the studies reporting ROM found a significant difference in hip motion, with female values greater than male values (**Table 4**). Boyer noted a greater peak hip adduction angle in females [8]. Furthermore, Cho et al. also described a significant difference in the mean angle across the gait cycle, with females more adducted. This is in agreement with previous research which demonstrates that females have a wider pelvis and a larger quadriceps angle (Q-angle) than males [73, 77, 78].

The three studies which reported hip ROM in the transverse plane over the full gait cycle found no significant differences between men and women (**Table 4**) [50, 53, 61] . However, both Hurd et al. [5] and Roislien et al. [79] found significantly different ROM during early stance. This also appears to be present in Figure 2g of Cho et al. [50] which shows a separation in peaks during initial stance. While this plot describes a ROM greater than typical normative values (e.g. [80]), these combined results suggest the need for further examination of transverse plane hip motion during early stance phase. Cho et al. also describes a mean difference over the gait cycle, with females more internally rotated than males. Again, this is likely a reflection of static, structural differences in femoral anteversion between the two sexes [72, 73, 81], also possibly resulting in the more internally rotated stance phase foot progression angle noted by Roislien et al. [79].

Table 4: Hip ROM

** indicates difference between the sexes ($p < .05$) and is given on the female value for the female/male pair. **Described during early stance. ***Oberg. et al. did not evaluate significance by decade age; average values are tabulated, and significance is described for all females as compared to all males. These authors also provided both left- and right-side measures; values reported here are averages of the two. 'D:' Indicates a derived ROM from published maximum and minimum values. Statistical significance in this case is based upon significance of either maximum or minimum published values. ¤ indicates that significance was not given and was not able to be derived. ± indicates a standard deviation and () indicates a SEM value. ʁTreadmill (T) or Overground (OG). 'SS' indicates a self-selected gait speed.*

					Range of Motion (deg)					
					Sagittal Plane		Coronal Plane		Transverse Plane	
Study	Speed	Age (years)	No. Subjects	T or OGʁ	Female	Male	Female	Male	Female	Male
Alton et al. 1998	Normal SS	20 - 29	17	OG	22 ± 4	26 ± 3				
			17	T	25 ± 4	28 ± 4				
Cho et al. 2004	Normal SS	20 - 29	98	OG	≈41¤	≈41	≈16¤	≈13	≈21¤	≈23
Chumanov et al. 2008	1.2 m/s	20 - 29	34	T			14 ± 3*	12±4	10 ± 2	9 ± 3
	1.5 m/s						15 ± 2*	12±2	11 ± 3	10 ± 3
	1.8 m/s						16 ± 2*	13±3	11 ± 4	11 ± 4
Crosbie and Vachalathiti 1997	Normal SS	40 - 59	108	OG	39 (1)	38 (1)				
	Fast SS				43 (1)	44 (1)				
Crosbie et al. 1997	Normal SS	<=50	85	OG	44 ± 4	48 ± 3				
		>50	43		43 ± 6	44 ± 5				
	Fast SS	<=50	85		53 ± 5	55 ± 4				
		>50	43		45 ± 7	47 ± 6				
Hurd et al. 2004**	Normal SS	20 - 29	20	OG	10 ± 4	8 ± 4	7 ± 2*	5 ± 2	6 ± 4*	2 ± 1
Kadaba et al. 1990	Normal SS	18 - 45	40	OG	Not significant		Significant difference*		Not significant	
Kerrigan et al. 1998	Normal SS	20 - 29	99	OG	46	44				
Ko et al. 2011	Normal SS	65 - 75	336	OG	39 ± 5*	41 ± 5	10 ± 3*	9 ± 3		
Oberg et al. 1994***	Slow SS	10 - 79	223	OG	42 ± 6	44 ± 6				
	Normal SS				47 ± 6¤	48 ± 6				
	Fast SS				51 ± 7¤	53 ± 7				
Roislien et al. 2009	Normal SS	23 - 62	48	OG					Significant difference*	

6.3 Knee

In the sagittal plane, six [5, 48, 50, 75, 76, 79] studies reported no significant differences in knee motion (**Table 5**), while Kerrigan et al. [62] and Kadaba et al. [61] reported females exhibited a significantly greater ROM than males. Boyer et al. [8], while not specifying ROM, noted that mid-stance knee flexion was greater in males. This conflicted information is too limited to state any generalizable trends or conclusions.

Of the four studies [5, 50, 61, 75] which presented coronal plane knee motion (Table 5), none found significant differences between males and females. Cho et al. [50] and Roislien et al. [79] both noted increased knee valgus throughout the gait cycle in women, likely due to increased Q-angles mentioned in conjunction with hip adduction.

Table 5: Knee ROM

** indicates difference between the sexes ($p < .05$) and is given on the female value for the female/male pair. **Described during early stance. ***Oberg. et al. did not evaluate significance by decade age; average values are tabulated, and significance is described for all females as compared to all males. These authors also provided both left- and right-side measures; values reported here are averages of the two. 'D:' Indicates a derived ROM from published maximum and minimum values. Statistical significance in this case is based upon significance of either maximum or minimum published values. ¤ indicates that significance was not given and was not able to be derived. ± indicates a standard deviation and () indicates a SEM value. ᴥTreadmill (T) or Overground (OG). 'SS' indicates a self-selected gait speed.*

					Range of Motion (deg)					
					Sagittal Plane		Coronal Plane		Transverse Plane	
Study	Speed	Age (years)	No. Subjects	T or OGᴥ	Female	Male	Female	Male	Female	Male
Alton et al. 1998	Normal SS	20 - 29	17	OG	57 ± 4	58 ± 4				
			17	T	56 ± 4	59 ± 3				
Cho et al. 2004	Normal SS	20 - 29	98	OG	D: 54	D: 54	≈15¤	≈12		
Hurd et al. 2004**	Normal SS	20 - 29	20	OG	14 ± 4	17 ± 4	4 ± 3	3 ± 2		
Kadaba et al. 1990	Normal SS	18 - 45	40	OG	Not significant		Not significant		Not significant	
Kerrigan et al. 1998	Normal SS	20 - 29	99	OG	D: 69*	D: 64				
Kettelkamp et al. 1970	Normal SS	20 - 35	22	OG	D: 50*	D: 46				
Ko et al. 2011	Normal SS	65 - 75	336	OG	54 ± 6	55 ± 6	10 ± 5	11 ± 4		
Oberg et al. 1994***	Slow SS	10 - 79	223	OG	D: 49	D: 50				
	Normal SS				D: 47	D: 48				
	Fast SS				D: 45	D: 44				
Roislien et al. 2009	Normal SS	23 - 62	48	OG	59¤	58				

6.4 Ankle

Six articles [48, 50, 61, 62, 75, 79] listed ROM for sagittal plane ankle motion (**Table 6**). Of these studies, Kerrigan et al. [62] and Ko et al. [75] found significant differences in ROM, with females exhibiting greater ROM than males. Though not reaching significance, females consistently demonstrated higher ROM values than males in the remaining studies, suggesting a trend in line with these two studies. Additionally, Boyer et al. [8] supported this by noting greater female ankle flexion at both heel strike and toe-off. Future research should examine this area, particularly during the stance/swing transition (e.g. Roislien et al. [79] and Cho et al. [50]). Newer multi-segment foot models may also help elucidate this possible difference.

Table 6: Ankle ROM

** indicates difference between the sexes ($p < .05$) and is given on the female value for the female/male pair. 'D:' Indicates a derived ROM from published maximum and minimum values. Statistical significance in this case is based upon significance of either maximum or minimum published values. ¤ indicates that significance was not given and was not able to be derived. ± indicates a standard deviation and () indicates a SEM value. ʬTreadmill (T) or Overground (OG). 'SS' indicates a self-selected gait speed.*

					Range of Motion (deg)					
					Sagittal Plane		Coronal Plane		Transverse Plane	
Study	Speed	Age (years)	No. Subjects	T or OGʬ	Female	Male	Female	Male	Female	Male
Alton et al. 1998	Normal SS	20 - 29	17	OG	34 ± 5	30 ± 6				
			17	T	32 ± 6	30 ± 4				
Cho et al. 2004	Normal SS	20 - 29	98	OG	D: 33	D: 30				
Kadaba et al. 1990	Normal SS	18 - 45	40	OG	Not significant		Not significant		Not significant	
Kerrigan et al. 1998	Normal SS	20 - 29	99	OG	D: 30*	D: 26				
Ko et al. 2011	Normal SS	65 - 75	336	OG	25 ± 5*	23 ± 5	10 ± 3	9 ± 3		
Roislien et al. 2009	Normal SS	23 - 62	48	OG	33¤	28				

6.5 Upper Body

In general, upper body motion during gait has received very little attention in the literature. Arm and shoulder differences between the sexes during gait have been virtually unexplored. The few studies reporting ROM sex differences have confined measures to the torso or thoracic spine.

In the sagittal plane, Goutier et al. [60] found torso ROM differences in young adults that were speed dependent (**Table 7**). At very slow speeds, torso flexion/extension was greater in females than in males, while at fast speeds male ROM was greater. No differences were found in Chung et al. [54] or the elderly groups of Goutier et al. However, Chung et al. did note a difference in the mean angles across the gait cycle, with women more extended than men in both the global and pelvis coordinate systems. This implies a greater lumbar lordosis in women that may have contributions from torso posture as well as the increased anterior pelvic tilt mentioned previously. Significant differences were not otherwise observed in the pelvic coordinate system.

In the coronal plane, no differences were found when analyzing torso motion relative to the global coordinate system in Chung et al. [57] or the elderly group of Goutier et al.

[60]. The younger group of Goutier et al. again demonstrated speed-dependent significant differences that were coupled with sagittal plane motion (**Table 7**); at very slow speeds, female torso motion exceeded males, while at fast self-selected speeds, males were greater. In the pelvic coordinate system, Chung et al. [54] showed a greater female torso ROM, which appears to be due to increased female pelvis ROM. Crosbie et al., on the other hand, found no differences at normal speeds but an increased ROM in male subjects over female subjects at fast speeds [56]. This finding is also primarily related to pelvis motion (see Table 3), with males exhibiting greater pelvic ROM than females in this study.

In the transverse plane (**Table 7**), no significant ROM differences were found in either of two studies [54, 56]. It should be noted that the ROM values presented by each of these studies are markedly different.

In a different method of analysis, Mazza et al. [64] analyzed sex differences in pelvis and upper body motion using the RMS accelerations of the pelvis, upper torso, and head. These authors found that females had greater mediolateral accelerations at the pelvis than males, similar values at the torso, and smaller values at the head. Likewise, in the sagittal plane, women exhibited similar pelvis and torso accelerations to men but less head accelerations. These differences were found both at preferred and fast walking speeds and suggest that females attenuate the accelerations arising from the lower extremities differently than males. These results also align with the conclusions of PLW studies which demonstrate sex identification during gait largely based upon differences in the pelvis and torso [18, 20]. To test if these attenuation control strategy differences exist in pre-pubertal children, the same authors repeated the acceleration study with subjects aged 8 - 11 years old [65]. They found that while accelerations were similar at the pelvis and torso, females again exhibited smaller values at the head in both the mediolateral and anterior-posterior directions. This comparison suggests a control strategy difference that is not entirely due to differing body mass distributions, compensations for greater pelvic motions, or gender-related habits such as walking with high heels.

Table 7: Torso ROM

Crosbie et al. (1997) also noted ROM of the lower torso. These authors indicated the only significant difference of their younger age group at the fast self-selected speed in the coronal plane. indicates difference between the sexes (p < .05). Where quantitative values were not reported, qualitative significance is given. ± indicates a standard deviation and () indicates a SEM value. [B]Treadmill (T) or Overground (OG). SS indicates a self-selected gait speed.*

						Range of Motion (deg)					
						Sagittal Plane		Coronal Plane		Transverse Plane	
	Study	Speed	Age (years)	No. Subjects	T or OG[B]	Female	Male	Female	Male	Female	Male
Relative to Ground	Chung et al. 2010	Normal SS	30 - 39	20	OG	4 ± 1	4 ± 2	3 ± 1	4 ± 1	8 ± 4	6 ± 2
Relative to Ground	Goutier et al. 2010[A]	0.8 m/s	20 - 29	20	OG	Female > male*		Female > male*			
Relative to Ground	Goutier et al. 2010[A]	1.2 m/s	20 - 29	20	OG	Not significant		Not significant			
Relative to Ground	Goutier et al. 2010[A]	1.6 m/s	20 - 29	20	OG	Female < male*		Female < male*			
Relative to Ground	Goutier et al. 2010[A]	2 m/s	20 - 29	20	OG	Female < male*		Female < male*			
Relative to Ground	Goutier et al. 2010[A]	0.8 m/s	70 - 79	20	OG	Not significant		Not significant			
Relative to Ground	Goutier et al. 2010[A]	1.2 m/s	70 - 79	20	OG	Not significant		Not significant			
Relative to Ground	Goutier et al. 2010[A]	1.6 m/s	70 - 79	20	OG	Not significant		Not significant			
Relative to Ground	Goutier et al. 2010[A]	2 m/s	70 - 79	20	OG	Not significant		Not significant			
Relative to Pelvis	Chung et al. 2010	Normal SS	30 - 39	20	OG	5 ± 2	4 ± 2	15 ± 5*	12 ± 4*	14 ± 5	14 ± 5
Relative to Pelvis	Crosbie et al. 1997	Normal SS	<= 50	85	OG	4 ± 2	4 ± 2	10 ± 4	10 ± 4	4 ± 2	5 ± 2
Relative to Pelvis	Crosbie et al. 1997	Normal SS	>50	43	OG	4 ± 3	3 ± 2	8 ± 3	9 ± 3	4 ± 2	5 ± 2
Relative to Pelvis	Crosbie et al. 1997	Fast SS	<=50	85	OG	5 ± 2	5 ± 2	11 ± 4*	13 ± 5	6 ± 1	6 ± 3
Relative to Pelvis	Crosbie et al. 1997	Fast SS	>50	43	OG	4 ± 2	4 ± 3	10 ± 5*	13 ± 5	4 ± 3	5 ± 2

6.6 Kinematics Discussion

Pelvic, and related hip joint, ROM in the coronal plane were consistently recognized as different between the sexes. While many individual studies suggested significant differences for other body segments and planes, the collective body of literature did not arrive at a clear consensus about these kinematic differences, and further research is needed to determine whether sex differences do indeed exist.

The studies reviewed herein agreed with psychology literature in finding that there were differences between the sexes in pelvic coronal plane motion. While Murray et al. [14] originally postulated that females ROM increases were "attitudinal," Mazza's [64, 65] results, in particular, suggested that there may be structural or motoric differences which influence the kinematic differences. Pelvic coronal plane ROM has been proposed as a mechanism to lower vertical center of mass (VCOM) excursions [82, 83]. Though greater exploration of age effects are needed, Smith et al. [67] showed that females had both greater pelvic obliquity and smaller VCOM than males, even when normalized to leg length. There may be other unexplored explanations for the differing pelvic kinematics between sexes; including differences in mass distributions or gluteal muscle properties (e.g. moment arms, fiber types, etc.).

Coronal plane hip motion was also consistently noted as significantly different, with females exhibiting a greater ROM than males. This is likely due simply to the greater ROM in coronal plane pelvis kinematics but should be verified. As previously mentioned, studies by Hurd et al. and Cho et al. indicate a difference in transverse plane hip motion during the initial loading of stance phase between men and women [5, 50]. Although these differences are lost when comparing ROM over the gait cycle, the influence of coronal plane hip motion on hip internal rotation during initial loading should be examined in greater detail.

Structural characteristics were often suggested as an explanation for kinematic differences, particularly when examining mean differences across the gait cycle. For example, Cho et al. [50] suggested that differences in sagittal plane hip motion were linked to the anterior tilt in the musculoskeletal structure of the female pelvis. Furthermore, these same authors wrote that the valgus position of the female knee may be due to the wider pelvis in females. This conclusion is also consistent with the description of larger Q-angle in females [77, 78]. The Q-angle is often pointed to as a means of explaining higher rates of knee pathology in females than males. These structural factors indicate inherent, biomechanical differences, rather than learned, lifestyle motivations for differences in gait.

In Murray's original study and in articles on human perception, coronal plane torso ROM was repeatedly identified as a key contributor in observers' abilities to detect sex or gender [2, 18, 20, 21, 84]. However, in the limited recent, quantitative studies, differences were equivocal. Clearly, there is a need to further explore this area. Upper extremity (i.e. shoulder/arm, elbow/forearm, and wrist/hand) analysis was also notably absent from this review. Virtually no information exists which compares these segments between sexes for non-pathological subjects. Though perception experiments [2] have found that upper-body joints are more indicative of sex than lower-extremity joints, there continues to be a dearth of data regarding upper extremity kinematics. Preliminary studies, such as those by Mazza et al. [64, 65], suggest that kinematic studies will reflect the trends established by the psychology field; however, more investigation is needed to fully quantify and describe upper-body differences between the sexes.

In describing kinematic differences and trends, there were a few studies which contradicted the majority of reviewed data. An example of this is the analysis of pelvic coronal plane motion. Though our analysis of reviewed articles established that females have a significantly greater ROM than males, the two studies by Crosbie directly go against this trend [55, 56]. These two studies, which seem to be drawn in part from the same dataset, each concluded that males have significantly greater pelvis ROM in the coronal plane than females and inverted the trend established by every other article quantifying pelvic coronal plane motion. We do not have an explanation for this discrepancy. Similar data mis-match is apparent in transverse plane hip motion (Cho et al. [50]) and torso motion relative to the ground (Goutier et al. [60]). Future kinematic studies should reference the trends and antagonists identified herein to establish true differences.

While biomechanical studies have focused almost exclusively on analysis of variance of discrete variables, additional insights might be found in alternate techniques. Time series or whole curve analyses might identify variables with sex differences confined only to portions of the gait cycle (e.g. hip rotation in early stance discussed above). Lessons might also be learned from other disciplines. Early perception articles examined individual walkers who were consistently misclassified as the opposite sex [1, 2] and used these to help guide their invariant theories. More thorough analysis of subjects who are either consistently classified correctly, or consistently misclassified, may provide insights into the continuum of sex differences. An example of this type of analysis is found in Johnson et al. [85], who examined androgynous walkers, finding that the dimorphic gait is related to both sex and gender identities, with gait providing both structural and cultural cues to an observer. A rapidly growing body of research in the computer vision field, with primary applications in surveillance, utilizes machine learning techniques to distinguish between males and females based on sets of variables or features (e.g. [86-89]). These classification techniques could be used to help identify the variable combinations, or analysis perspectives, that are most important in distinguishing gender [84, 90]. Alternatively, biomechanical insights might be used to guide machine learning approaches [91]. Finally, although some individual variables did not show significant differences between the sexes, these same variables may have subtle contributions to sex differentiation when used in combination with other variables, providing additional insights not obtainable through traditional analysis.

A limitation to the current body of knowledge is the myopic view of the impact of culture and lifestyle on gait. The minority of studies which noted the effect of these factors [27, 58, 66] found many significant differences. As previously discussed (see page 12 - Spatiotemporal Discussion), initial studies have found significant differences when comparing spatiotemporal metrics between cultures. While these studies relate the effects of lifestyle, culture, and time of testing on spatiotemporal values, these implications are unexplored for kinematic parameters. Additionally, most studies cited herein select subjects from a homogeneous group. Kinematic studies specifically focused on non-typical populations (e.g. subjects taken from a non-academic environment) should be examined in future work.

7.0 REFERENCES

1. Barclay, C.D., J.E. Cutting, and L.T. Kozlowski, Temporal and spatial factors in gait perception that influence gender recognition. Perception & psychophysics, 1978. **23**(2): 145-152.
2. Kozlowski, L. and J. Cutting, Recognizing the sex of a walker from a dynamic point-light display. Perception & Psychophysics, 1977. **21**(6): 575-580.
3. Arendt, E. and R. Dick, Knee Injury Patterns Among Men and Women in Collegiate Basketball and Soccer: NCAA Data and Review of Literature. The American Journal of Sports Medicine, 1995. **23**(6): 694-701.
4. Ferretti, A., et al., Knee ligament injuries in volleyball players. The American Journal of Sports Medicine, 1992. **20**(2): 203-207.
5. Hurd, W.J., et al., Differences in normal and perturbed walking kinematics between male and female athletes. Clin Biomech (Bristol, Avon), 2004. **19**(5): 465-472.
6. Csapo, R., et al., On muscle, tendon and high heels. The Journal of Experimental Biology, 2010. **213**(15): 2582-2588.
7. McKean, K.A., et al., Gender differences exist in osteoarthritic gait. Clinical Biomechanics, 2007. **22**(4): 400-409.
8. Boyer, K.A., G.S. Beaupre, and T.P. Andriacchi, Gender differences exist in the hip joint moments of healthy older walkers. Journal of biomechanics, 2008. **41**(16): 3360-3365.
9. de Lau, L.M.L. and M.M.B. Breteler, Epidemiology of Parkinson's disease. The Lancet Neurology, 2006. **5**(6): 525-535.
10. Haaxma, C.A., et al., Gender differences in Parkinson’s disease. Journal of Neurology, Neurosurgery & Psychiatry, 2007. **78**(8): 819-824.
11. Ding, E.L., et al., Sex differences of endogenous sex hormones and risk of type 2 diabetes. JAMA: the journal of the American Medical Association, 2006. **295**(11): 1288-1299.
12. Meisinger, C., et al., Sex differences in risk factors for incident type 2 diabetes mellitus: the MONICA Augsburg cohort study. Arch Intern Med, 2002. **162**(1): 82-89.
13. Murray, M.P., et al., Comparison of free and fast speed walking patterns of normal men. Am J Phys Med, 1966. **45**(1): 8-23.
14. Murray, M.P., R.C. Kory, and S.B. Sepic, Walking patterns of normal women. Arch Phys Med Rehabil, 1970. **51**(11): 637-650.
15. Booyens, J. and W. Keatinge, The expenditure of energy by men and women walking. The Journal of physiology, 1957. **138**(2): 165-171.
16. Cutting, J. and D. Proffitt, Gait Perception as an Example of How We May Perceive Events, in Intersensory Perception and Sensory Integration, R. Walk and H. Pick, Jr., Editors. 1981, Springer US. 249-273.
17. Cutting, J.E., Generation of synthetic male and female walkers through manipulation of a biomechanical invariant. Perception, 1978. **7**(4): 393-405.
18. Cutting, J.E., D.R. Proffitt, and L.T. Kozlowski, A biomechanical invariant for gait perception. J Exp Psychol Hum Percept Perform, 1978. **4**(3): 357-372.

19. Chiu, M.C. and M.J. Wang, The effect of gait speed and gender on perceived exertion, muscle activity, joint motion of lower extremity, ground reaction force and heart rate during normal walking. Gait Posture, 2007. **25**(3): 385-392.
20. Mather, G. and L. Murdoch, Gender discrimination in biological motion displays based on dynamic cues. Proceedings of the Royal Society of London. Series B: Biological Sciences, 1994. **258**(1353): 273-279.
21. Johnson, K.L. and L.G. Tassinary, Perceiving sex directly and indirectly: meaning in motion and morphology. Psychol Sci, 2005. **16**(11): 890-897.
22. Yu, S., et al., A study on gait-based gender classification. IEEE Trans Image Process, 2009. **18**(8): 1905-1910.
23. Saunders, D.R., D.K. Williamson, and N.F. Troje, Gaze patterns during perception of direction and gender from biological motion. J Vis, 2010. **10**(11): 9.
24. Laufer, Y., Age- and gender-related changes in the temporal-spatial characteristics of forwards and backwards gaits. Physiother Res Int, 2003. **8**(3): 131-142.
25. Lusardi, M.M., Using Walking Speed in Clinical Practice: Interpreting Age-, Gender-, and Function-Specific Norms. Topics in Geriatric Rehabilitation, 2012. **28**(2): 77-90 10.1097/TGR.1090b1013e31823d31827b31829f.
26. Bohannon, R.W. and A. Williams Andrews, Normal walking speed: a descriptive meta-analysis. Physiotherapy, 2011. **97**(3): 182-189.
27. Al-Obaidi, S., et al., Basic gait parameters: a comparison of reference data for normal subjects 20 to 29 years of age from Kuwait and Scandinavia. J Rehabil Res Dev, 2003. **40**(4): 361-366.
28. Aniansson, A., A. Rundgren, and L. Sperling, Evaluation of functional capacity in activities of daily living in 70-year-old men and women. Scand J Rehabil Med, 1980. **12**(4): 145-154.
29. Atkinson, H.H., et al., Cognitive function, gait speed decline, and comorbidities: the health, aging and body composition study. J Gerontol A Biol Sci Med Sci, 2007. **62**(8): 844-850.
30. Ble, A., et al., Executive function correlates with walking speed in older persons: the InCHIANTI study. J Am Geriatr Soc, 2005. **53**(3): 410-415.
31. Bohannon, R.W., Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. Age Ageing, 1997. **26**(1): 15-19.
32. Bohannon, R.W., Population representative gait speed and its determinants. J Geriatr Phys Ther, 2008. **31**(2): 49-52.
33. Bohannon, R.W., A.W. Andrews, and M.W. Thomas, Walking speed: reference values and correlates for older adults. J Orthop Sports Phys Ther, 1996. **24**(2): 86-90.
34. Brach, J.S., et al., Gait variability and the risk of incident mobility disability in community-dwelling older adults. J Gerontol A Biol Sci Med Sci, 2007. **62**(9): 983-988.
35. Callisaya, M.L., et al., Sex modifies the relationship between age and gait: a population-based study of older adults. J Gerontol A Biol Sci Med Sci, 2008. **63**(2): 165-170.
36. DePasquale, L. and L. Toscano, The Spring Scale Test: a reliable and valid tool for explaining fall history. J Geriatr Phys Ther, 2009. **32**(4): 159-167.

37. Fitzpatrick, A.L., et al., Associations of gait speed and other measures of physical function with cognition in a healthy cohort of elderly persons. J Gerontol A Biol Sci Med Sci, 2007. **62**(11): 1244-1251.

38. Freiberger, E., et al., Preventing falls in physically active community-dwelling older people: a comparison of two intervention techniques. Gerontology, 2007. **53**(5): 298-305.

39. Nagasaki, H., et al., Walking patterns and finger rhythm of older adults. Percept Mot Skills, 1996. **82**(2): 435-447.

40. Oberg, T., A. Karsznia, and K. Oberg, Basic gait parameters: reference data for normal subjects, 10-79 years of age. J Rehabil Res Dev, 1993. **30**(2): 210-223.

41. Obuchi, S., et al., Relationship between walking ability and risk of falls in community dwelling elderly in Japan. J Phys Ther Sci, 1994. **6**: 39-44.

42. Purser, J.L., et al., Trajectories of leg strength and gait speed among sedentary older adults: longitudinal pattern of dose response. J Gerontol A Biol Sci Med Sci, 2003. **58**(12): M1125-1134.

43. Steffen, T.M., T.A. Hacker, and L. Mollinger, Age- and gender-related test performance in community-dwelling elderly people: Six-Minute Walk Test, Berg Balance Scale, Timed Up & Go Test, and gait speeds. Phys Ther, 2002. **82**(2): 128-137.

44. Tiedemann, A., C. Sherrington, and S.R. Lord, Physiological and psychological predictors of walking speed in older community-dwelling people. Gerontology, 2005. **51**(6): 390-395.

45. van Iersel, M.B., M.G. Olde Rikkert, and G.F. Borm, A method to standardize gait and balance variables for gait velocity. Gait & posture, 2007. **26**(2): 226-230.

46. Willen, C., et al., How is walking speed related to muscle strength? A study of healthy persons and persons with late effects of polio. Arch Phys Med Rehabil, 2004. **85**(12): 1923-1928.

47. Wolfson, L., et al., Balance and strength training in older adults: intervention gains and Tai Chi maintenance. J Am Geriatr Soc, 1996. **44**(5): 498-506.

48. Alton, F., et al., A kinematic comparison of overground and treadmill walking. Clin Biomech (Bristol, Avon), 1998. **13**(6): 434-440.

49. Barrett, R., M.V. Noordegraaf, and S. Morrison, Gender differences in the variability of lower extremity kinematics during treadmill locomotion. J Mot Behav, 2008. **40**(1): 62-70.

50. Cho, S.H., J.M. Park, and O.Y. Kwon, Gender differences in three dimensional gait analysis data from 98 healthy Korean adults. Clin Biomech (Bristol, Avon), 2004. **19**(2): 145-152.

51. Chockalingam, N., et al., Comparison of pelvic complex kinematics during treadmill and overground walking. Arch Phys Med Rehabil, 2012. **93**(12): 2302-2308.

52. Chui, K.K. and M.M. Lusardi, Spatial and temporal parameters of self-selected and fast walking speeds in healthy community-living adults aged 72-98 years. J Geriatr Phys Ther, 2010. **33**(4): 173-183.

53. Chumanov, E.S., C. Wall-Scheffler, and B.C. Heiderscheit, Gender differences in walking and running on level and inclined surfaces. Clin Biomech (Bristol, Avon), 2008. **23**(10): 1260-1268.

54. Chung, C.Y., et al., Kinematic aspects of trunk motion and gender effect in normal adults. J Neuroeng Rehabil, 2010. **7**: 9.
55. Crosbie, J. and R. Vachalathiti, Synchrony of pelvic and hip joint motion during walking. Gait & Posture, 1997. **6**(3): 237-248.
56. Crosbie, J., R. Vachalathiti, and R. Smith, Age, gender and speed effects on spinal kinematics during walking. Gait & Posture, 1997. **5**(1): 13-20.
57. Eke-Okoro, S. and B. Sandlund, The effects of load, shoes, sex and direction on the gait characteristics of street pedestrians. J Hum Move Stud, 1984. **10**: 107-114.
58. Finley, F.R. and K.A. Cody, Locomotive characteristics of urban pedestrians. Arch Phys Med Rehabil, 1970. **51**(7): 423-426.
59. Forczek, W. and R. Staszkiewicz, An evaluation of symmetry in the lower limb joints during the able-bodied gait of women and men. J Hum Kinet, 2012. **35**: 47-57.
60. Goutier, K.M., et al., The influence of walking speed and gender on trunk sway for the healthy young and older adults. Age Ageing, 2010. **39**(5): 647-650.
61. Kadaba, M.P., H.K. Ramakrishnan, and M.E. Wootten, Measurement of lower extremity kinematics during level walking. J Orthop Res, 1990. **8**(3): 383-392.
62. Kerrigan, D.C., M.K. Todd, and U. Della Croce, Gender differences in joint biomechanics during walking: normative study in young adults. Am J Phys Med Rehabil, 1998. **77**(1): 2-7.
63. Kettelkamp, D.B., et al., An electrogoniometric study of knee motion in normal gait. J Bone Joint Surg Am, 1970. **52**(4): 775-790.
64. Mazza, C., et al., Gender differences in the control of the upper body accelerations during level walking. Gait Posture, 2009. **29**(2): 300-303.
65. Mazza, C., M. Zok, and A. Cappozzo, Head stabilization in children of both genders during level walking. Gait Posture, 2010. **31**(4): 429-432.
66. Sato, H. and K. Ishizu, Gait patterns of Japanese pedestrians. J Hum Ergol (Tokyo), 1990. **19**(1): 13-22.
67. Smith, L.K., J.L. Lelas, and D.C. Kerrigan, Gender differences in pelvic motions and center of mass displacement during walking: stereotypes quantified. J Womens Health Gend Based Med, 2002. **11**(5): 453-458.
68. Sekiya, N. and H. Nagasaki, Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio (step-length/step-rate). Gait & Posture, 1998. **7**(3): 225-227.
69. Hollman, J.H., E.M. McDade, and R.C. Petersen, Normative spatiotemporal gait parameters in older adults. Gait & posture, 2011. **34**(1): 111-118.
70. Senden, R., et al., Importance of correcting for individual differences in the clinical diagnosis of gait disorders. Physiotherapy, 2012. **98**(4): 320-324.
71. Hertel, J., J.H. Dorfman, and R.A. Braham, Lower extremity malalignments and anterior cruciate ligament injury history. J Sports Sci Med, 2004. **3**(4): 220-225.
72. McKeon, J.M.M. and J. Hertel, Sex differences and representative values for 6 lower extremity alignment measures. Journal of athletic training, 2009. **44**(3): 249.

73. Nguyen, A.-D. and S.J. Shultz, Sex differences in clinical measures of lower extremity alignment. The Journal of orthopaedic and sports physical therapy, 2007. **37**(7): 389.
74. Saunders, J.B., V.T. Inman, and H.D. Eberhart, The major determinants in normal and pathological gait. J Bone Joint Surg Am, 1953. **35-A**(3): 543-558.
75. Ko, S.-u., et al., Sex-specific differences in gait patterns of healthy older adults: Results from the Baltimore Longitudinal Study of Aging. Journal of biomechanics, 2011. **44**(10): 1974-1979.
76. Oberg, T., A. Karsznia, and K. Oberg, Joint angle parameters in gait: reference data for normal subjects, 10-79 years of age. J Rehabil Res Dev, 1994. **31**(3): 199-213.
77. Aglietti, P., J.N. Insall, and G. Cerulli, Patellar pain and incongruence. I: Measurements of incongruence. Clin Orthop Relat Res, 1983(176): 217-224.
78. Horton, M.G. and T.L. Hall, Quadriceps femoris muscle angle: normal values and relationships with gender and selected skeletal measures. Phys Ther, 1989. **69**(11): 897-901.
79. Roislien, J., et al., Simultaneous estimation of effects of gender, age and walking speed on kinematic gait data. Gait Posture, 2009. **30**(4): 441-445.
80. Perry, J. and J.M. Burnfield, Gait Analysis: Normal and Pathological Function. 2010: Slack Incorporated.
81. Bråten, M., T. Terjesen, and I. Rossvoll, Femoral anteversion in normal adults: ultrasound measurements in 50 men and 50 women. Acta Orthopaedica, 1992. **63**(1): 29-32.
82. Inman, V.T. and H.D. Eberhart, The major determinants in normal and pathological gait. The Journal of Bone & Joint Surgery, 1953. **35**(3): 543-558.
83. Kerrigan, D.C., et al., Quantification of pelvic rotation as a determinant of gait. Archives of physical medicine and rehabilitation, 2001. **82**(2): 217-220.
84. Troje, N.F., Decomposing biological motion: a framework for analysis and synthesis of human gait patterns. J Vis, 2002. **2**(5): 371-387.
85. Johnson, K.L., et al., Swagger, sway, and sexuality: Judging sexual orientation from body motion and morphology. J Pers Soc Psychol, 2007. **93**(3): 321-334.
86. Lee, L., Gait dynamics for recognition and classification. 2001.
87. Lee, L. and W. Grimson. Gait analysis for recognition and classification. in Automatic Face and Gesture Recognition, 2002. Proceedings. Fifth IEEE International Conference on. 2002. IEEE.
88. Li, X., et al., Gait components and their application to gender recognition. Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, 2008. **38**(2): 145-155.
89. Ng, C.B., Y.H. Tay, and B.M. Goi, Vision-based Human Gender Recognition: A Survey. arXiv preprint arXiv:1204.1611, 2012.
90. Livne, M., et al., Human attributes from 3D pose tracking. Computer Vision and Image Understanding, 2012. **116**(5): 648-660.
91. Davis, J.W. and H. Gao, An expressive three-mode principal components model for gender recognition. Journal of Vision, 2004. **4**(5).

92. Bessou, P., et al., Simultaneous recording of longitudinal displacements of both feet during human walking. Journal de physiologie, 1989. **83**(2): 102.
93. Chao, E., et al., Normative data of knee joint motion and ground reaction forces in adult level walking. Journal of biomechanics, 1983. **16**(3): 219-233.
94. Hageman, P.A. and D.J. Blanke, Comparison of gait of young women and elderly women. Physical Therapy, 1986. **66**(9): 1382-1387.
95. Blanke, D.J. and P.A. Hageman, Comparison of gait of young men and elderly men. Physical Therapy, 1989. **69**(2): 144-148.
96. Richard, R., et al., Spatiotemporal gait parameters measured using the Bessou gait analyzer in 79 healthy subjects. Influence of age, stature, and gender. Study Group on Disabilities due to Musculoskeletal Disorders (Groupe de Recherche sur le Handicap de l'Appareil Locomoteur, GRHAL). Revue du rhumatisme (English ed.), 1995. **62**(2): 105.
97. Waters, R.L., et al., Energy-speed relationship of walking: standard tables. Journal of Orthopaedic Research, 1988. **6**(2): 215-222.

LIST OF ACRONYMS

CoM	Center of Movement
D	Derived from published maximum and minimum values
OG	Overground
PLW	Point-Light Walkers
ROM	Range of Motion
SS	Self-Selected Speed
T	Treadmill