Spatiotemporal and plantar pressure gait patterns of 1000 healthy individuals aged 3-101 years

Marnee J. McKay[a], Jennifer N. Baldwin[a] , Paulo Ferreira[a] , Milena Simic[a] , Natalie Vanicek[b] , Elizabeth Wojciechowski[c] , Anita Mudge[c] , Joshua Burnsa[c]

[a] The University of Sydney, Musculoskeletal Health, Faculty of Health Sciences, Sydney, New South Wales, Australia

[b] Department of Sport, Health and Exercise Science, School of Life Sciences, University of Hull, United Kingdom

[c] Paediatric Gait Analysis Service of New South Wales, Sydney Children's Hospitals Network (Randwick and Westmead), New South Wales, Australia

Published in: *Gait and Posture* 2017; 58: 78- 87

http://dx.doi.org/10.1016/j.gaitpost.2017.07.004

Abstract

Objective. The purpose of this study was to establish normative reference values for spatiotemporal and plantar pressure parameters and to investigate the influence of demographic, anthropometric and physical characteristics.

Methods. In 1000 healthy males and females aged 3-101 years, spatiotemporal and plantar pressure data were collected barefoot with the Zeno^{TM} walkway and Emed$^{®}$ platform. Correlograms were developed to visualise the relationships between widely reported spatiotemporal and pressure variables with demographic (age, gender), anthropometric (height, mass, waist circumference) and physical characteristics (ankle strength, ankle range of motion, vibration perception) in children aged 3-9 years, adolescents aged 10-19 years, adults aged 20-59 years and older adults aged over 60 years.

Results. A comprehensive catalogue of 31 spatiotemporal and plantar pressure variables were generated from 1000 healthy individuals. The key findings were that gait velocity was stable during adolescence and adulthood, while children and older adults walked at a comparable slower speed. Peak pressures increased during childhood to older adulthood. Children demonstrated highest peak pressures beneath the rearfoot whilst adolescents, adults and older adults demonstrated highest pressures at the forefoot. Main factors influencing spatiotemporal and pressure parameters were: age, height, body mass and waist circumference, as well as ankle dorsiflexion and plantarflexion strength.

Conclusion. This study has established whole of life normative reference values of widely used spatiotemporal and plantar pressure gait parameters and revealed changes to be expected across the lifespan.

Introduction

Gait is a meaningful outcome measure used to identify pathology, evaluate disease progression and measure the efficacy of interventions [1]. Gait impairments are frequently investigated in children and adults with neurological diseases [2-5], children with developmental delay and neurodevelopment disorders [6, 7] and in those affected by musculoskeletal conditions [8, 9]. Spatiotemporal parameters are utilised to evaluate people at risk of falls [10-12], evaluate impairments associated with neurofibromatosis [13] and assess effectiveness of orthoses for hemiparesis [14]. Gait velocity alone is predictive of future morbidity and mortality as well as a generic indicator of health status [15]. Pedobarography is often collected to assess outcomes of foot surgery [16-19], offloading interventions in managing diabetic foot ulcers [20], evaluate conservative management of clubfoot [21] and design footwear for people suffering neuropathic foot pain [22] and painful pes cavus [23].

To identify atypical spatiotemporal and plantar pressure patterns, access to reliable age-matched normative reference data are required. Reference values of spatiotemporal and plantar pressure parameters can facilitate the diagnosis of pathologies and guide clinical decisions to personalise treatment. Normative data contribute to the development of responsive outcome measures and serve as important comparators to monitor the effectiveness of interventions. Progress in the fields of rehabilitation and gait retraining depend on generating more sensitive and objective outcome measures of gait [24]. However, current normative datasets of spatiotemporal and plantar pressure values are limited by small cohorts [25-28] and specific age groups, namely children [29-34] or adults over 70 years of age [35, 36]. Whole of life data collected from a large age- and sex-stratified population, using standardised procedures, equipment, personnel and analysis strategy will fill the knowledge gaps in normative gait parameters to assess the severity of pathology and response to rehabilitative and surgical therapies. Therefore, the primary aim of this study was to generate a comprehensive dataset of reference values, stratified for age and sex. The secondary aim was to investigate the relationship between demographic, anthropometric and physical characteristics on spatiotemporal and plantar pressure parameters.

Methods and Materials

Participants

Data were collected from January 2014 to September 2015 as part of the 1000 Norms Project, a cross-sectional observational study investigating gait, physical capability and self-reported health in 1000 healthy individuals aged 3-101 years (see full protocol [37]). Eligible participants were healthy by self-report and able to participate in age-appropriate activities. Individuals with health conditions affecting physical performance, including diabetes mellitus, infectious or inflammatory arthropathies, body mass index ≥40 kg/m^2 and neurological disorders were excluded. One thousand individuals living in the Greater Sydney metropolitan area in Australia were recruited using a structured convenience sampling approach through government and community groups, educational institutions and aged care independent living facilities. The sample was stratified for age and gender with oversampling of children to capture important developmental changes. Twenty children per year from 3-9 years and 16 per year from 10-19 years were recruited, as well as 100 people per decade in the age groups of: 20-29, 30-39, 40-49, 50-59, 60-69 70-79 and 80+ years. The study was granted institutional ethics approval (#2013/640) and participants provided informed written consent.

Procedure

All measures were collected by two experienced physiotherapists (M.J.M and J.N.B). The dominant lower limb was assessed and determined as the foot used to kick a ball. Participants provided demographic information, including ethnicity and had their height, body mass, waist circumference, foot structure and lower limb alignment assessed. Foot structure was evaluated using the Foot Posture Index, a six-item scale from -12 (supinated) to +12 (pronated). Lower limb alignment was assessed in standing using a digital inclinometer (varus alignment recorded as positive and valgus negative).

Spatiotemporal and plantar pressure measures

Participants completed five walks across a Zeno^{TM} pressure sensitive walkway (Protokinetics, Havertown, PA, US) embedded with sensors sampling at 120 Hz. Participants walked at their 'comfortable walking pace' starting and ending 2.5m before and after the walkway to allow for initial acceleration and terminal deceleration.

Plantar pressures were collected using Emed®-AT/2 capacitance pressure distribution platform embedded in a flat dense rubber walkway (Novel GmbH, Munich, Germany), sensor area 360mm x 190mm containing 1377 sensors, resolution 2 sensors/cm^2 (recording frequency 25Hz). Three walks at comfortable pace were collected using the two-step protocol, whereby participants strike the platform with their dominant foot and continue walking for two-three steps [38]. The two-step approach is comparable with the midgait method in young children and preferable in terms of ease and speed of data collection [39]. Children and older adults were afforded extra practice sessions where necessary and trials were excluded for deliberate targeting or pausing. To ensure the sampling frequency and sensor resolution of the Emed®-AT/2 was adequate, we compared it to the Emed®-X (frequency 100Hz, resolution 4 sensors/cm^2) at the Paediatric Gait Analysis Service of New

South Wales, Sydney Children's Hospitals Network-Westmead (Human Research Ethics Committee #LNR/12/SCHN/146, unpublished data). Ten participants age 22-50 years walked 3 times over both the Emed®-AT/2 and Emed®-X. Pressure, force and spatiotemporal values were highly correlated between platforms: maximum mean pressure (r=.96, p<.001), peak pressure (r=.93, p<.001), pressure-time integral (r=.93, p<.001), maximum force (r=.70, p=.024), contact area (r=.98, p<.001) and contact time (r=.87, p=.001). To check the sensor resolution of the Emed®-AT/2 was acceptable for smaller feet, we collected data using the Emed®-X in 10 children aged 9-16 years and transformed the data to the Emed®-AT/2 equivalent sensor resolution of 2 sensors/cm^2 using Novel Scientific software package (version 22) (Novel GmbH, Munich, Germany). Pressure, force and spatiotemporal values were highly correlated: maximum mean pressure, (r=.998, p<.001), peak pressure (r=.970, p<.001), pressure-time integral (r=.988, p<.001), maximum force (r=.1.0, p<.001), contact area (r=.995, p<.001) and contact time (r=.1.0, p<.001).

Physical characteristics

Vibration perception as a measure of sensation, ankle range of motion (ROM) and strength were assessed in accordance with the 1000 Norms Project protocol [37]. Vibration perception using the Rydel-Seiffer tuning fork was defined as normal or abnormal according to perception of vibration ≥5 at the great toe. Ankle plantarflexion ROM was assessed using a goniometer non-weight bearing, and dorsiflexion was assessed using the weight-bearing lunge test. Ankle dorsiflexion/plantarflexion strength was assessed by maximal voluntary isometric contraction using a hand-held dynamometer (Citec CT 3001, CIT Technics, Groningen, Netherlands) in long sitting. Hallux and lesser toes strength were assessed using the Paper Grip Test (PGT) and a composite score out of six was summed based on the number of successful trials of PGT-1 (hallux strength) and PGT-2 (lesser toes strength). Interrater reliability between evaluators demonstrated satisfactory repeatability of all strength and ROM measures ($ICC_{2,1}$ 0.80–0.99) in 10 participants aged 6-67 years.

Data processing

Fifteen spatiotemporal parameters from the Zeno^{TM} were generated using ProtoKinetics Movement Analysis Software (PKMAS) version5.07C7c. Sixteen pressure variables were generated using Novel Scientific software package (version 22) (Novel GmbH, Munich, Germany). Pressure data were analysed for the whole foot and three 'masks' dividing the foot into anatomically relevant regions based on skeletal measurements to allow consistent and repeatable divisions of all feet [40]. The rearfoot was defined as 31% of foot length, midfoot 19% and the forefoot 50%. Foot progression angle was accounted for during analysis by the Novel software, with each foot rotated to a common set of coordinate axes. See Supplement 1 for the definition of all spatiotemporal and plantar pressure variables.

Statistical analysis

Descriptive reference values, stratified for age and sex, for the 31 spatiotemporal and pressure variables were calculated in SPSS v22 (IBM SPSS Statistics for Windows, Armonk, NY, US). Normality of the data was assessed using the Kolmorgorov-Smirnov test and the appropriate parametric or non-parametric test applied. For inferential analysis, World Health Organization age group classifications were used: children (age 3-9 years), adolescents (age 10-19 years), adults (age 20-59 years) and older adults (age 60-101 years). The role of maturation in the variation of gait parameters is unclear, as is the age at which mature gait is achieved, consequently no single variable was adjusted for in the analysis of any age group.[31, 41, 42] To determine if spatiotemporal and plantar pressure variables differed between males and females, independent sample t-tests were conducted for each age group. Differences between age groups were evaluated using one-way ANOVA with Tukey's post hoc for widely reported spatiotemporal parameters [velocity (cm/s), stride length (cm), stride width (cm), cadence (steps/min), and double support time as percentage of gait cycle]and pressure variables [maximum mean pressure (kPa), peak pressure (kPa), pressure-time integral [(kPa)*s], maximum force (N), force- time integral (N*s), contact area (cm^2) and contact time (s)]. A series of correlograms were constructed based on Pearson product-moment correlation coefficients (r) to explore the bivariate relationships between these key spatiotemporal and pressure parameters and demographic, anthropometric and physical characteristics (age, height, body mass, waist circumference, foot posture index, lower limb alignment, sensation, ankle range and strength, toe strength). Results were considered significant if p<.05. To reduce the likelihood of type II errors Bonferroni correction was not undertaken [43]

Results

Physical and sociodemographic characteristics of the sample are provided in Supplement 2. Key spatiotemporal gait parameters for children, adolescents, adults and older adults are presented in Table 1. Normative reference values (normalized and non-normalized) for 15 spatiotemporal gait parameters according to age group per decade and sex are presented in Supplement 3. There was no gender difference (p<.05) in gait velocity in any age category. Gait velocity was stable during adolescence and adulthood, while children and older adults walked at a comparable slower speed (Supplement 4). There was no significant difference between boys and girls aged 3-9 years for any gait parameter. From adolescence to older adulthood, males exhibited longer stride length and in adulthood males had greater stride width compared to females (p<.05). Females had higher cadence rates than males from adolescence, and children recorded the highest cadence rate. Children spent the least amount of time in double support phase of the gait cycle and older adults spent the most (Supplement 4).

Normative reference values for the 16 pressure variables according to age group per decade and sex are presented in Supplement 5. Key pressure parameters for children, adolescents, adults and older adults are presented in Table 1. Peak pressures increased during childhood to older adulthood. Children demonstrated highest peak pressures beneath the rearfoot whilst adolescents, adults and older adults demonstrated highest pressures under the forefoot (Supplement 4). There were no significant differences between the plantar pressure patterns of boys and girls aged 3-9 years. From adolescence, males demonstrated higher maximum force, force-time integrals and contact area compared to females as well as significantly greater pressure-time integrals in adulthood. All plantar pressure and force variables under the whole foot increased with age, were significantly different between all age categories and greatest in older adults, with the exception of maximum force where no differences were present between adults and older adults. Older adults also demonstrated significantly greater contact time compared to children, adolescents and adults (Supplement 4).

Correlograms depicting relationships between gait variables and demographic and physical characteristics are presented in Figures 1-4. During childhood, increasing age correlated with longer stride length ($r=.752$, $p<.01$), faster gait velocity ($r=.366$, $p<.01$), higher peak pressure (rearfoot $r=.506$, forefoot $r=.595$ and whole foot $r=.568$, $p<.01$) and maximum force value (rearfoot $r=.784$, midfoot $r= .218$, forefoot $r=.808$, whole foot $r=.788$ $p=<.01$). During adolescence, the influence of age on spatiotemporal and pressure variables reduced ($r=.180$, $p=.023$ to $r=.576$, $p<.001$) and in adults, the impact of age on spatiotemporal and pressure variables was low ($r=.106$, $p=.033$ to $r=.221$, $p<.001$) or no longer significant. During older adulthood age was associated with greater double support phase ($r=.327$, $p<.001$), shorter stride length (r= -.355, p<.001), slower walking speed (r= -.327, p<.001) and increased contact time (r=.384, p<.001).

Height and body mass correlated with gait variables across all ages (Figures 1-4). As expected, greater height was associated with longer stride length and lower cadence. Greater body mass and waist circumference was associated with lower cadence and wider stride width, as well as higher plantar pressures and greater contact area in all age groups. Pronated foot posture, according to the Foot Posture Index, was marginally associated with increased contact area (r=.209, p=.013) and contact time (r=.236, p=.005) in children and increased peak pressure beneath the whole foot (r=.259, p<.001) in older adults. Varus lower limb alignment was also marginally associated with greater rearfoot, forefoot and whole foot force- and pressure-time integrals (r=.176, p=.039 to r =.274, p=.001) in children and increased stride width in adolescents through to older adults (r = -.216, p=.006 to r =.289, p<.001).

Relationships between gait and vibration perception were only significant in older adults. Decreased ability to perceive vibration was associated with lower cadence and slower gait velocity, increased maximum force beneath the forefoot and whole foot as well as force-time integrals (with the exception of the midfoot) and increased contact area, although the strength of these associations was low (r=.120, p=.038 to r=-.235, p<.001). Greater dorsiflexion ROM was associated with longer stride length (r=.375, p<.001) and gait velocity (r= .266, p<.001) in older adults, whilst greater dorsiflexion strength was significantly associated with longer stride length (r=.635, p<.001) and gait velocity (r=.323 p<.001) in children (Figures 4 and 1). Dorsiflexion and plantarflexion strength were associated with increased plantar pressures beneath the whole foot, rearfoot and forefoot (r =.196 p=.021 to r=.758, p<.001) in children. By older adulthood these associations were most notably present in measures of maximum force (r=.284, p<.001 to r=.421, p<.001). Strong dorsiflexors, plantarflexors and toe flexors were associated with greater stride length in all age categories (r=.155, p=.002 to .641, p<.001). Correlations between toe flexor strength and plantar pressure were most evident in children (r=.239, p=.005 to .473, p<.001).

Discussion

We describe the generation of the most comprehensive catalogue of spatiotemporal and plantar pressure variables to date, incorporating biomechanical data from 1000 healthy individuals aged 3-101 years using standardised procedures, equipment, personnel and data analysis strategy. Gait velocity was stable from adolescence through to adulthood and there was no difference in the self-selected gait velocity of children and older adults. Peak pressure increased from childhood through to older adulthood, however children demonstrated highest pressures beneath the rearfoot whilst adolescents, adults and older adults recorded highest pressures at the forefoot. Measures of gait were associated with age, height, mass, waist circumference, and ankle strength.

Velocity is the most commonly reported gait variable and is often selected as the primary outcome in trials involving gait analysis [1]. The gait velocity for older adults (1.18 ±.20 m/s) is consistent with previous studies with similar exclusion/inclusion criteria such as the Dynamics of Health, Ageing and Body Composition Study (1.17±.24 m/s) [44]. The percentage of time older adults spent in double support phase was in agreement with values reported in the literature, however our older adults demonstrated higher cadence and smaller stride width [35, 36, 45]. Our findings are consistent with Lythgo et al [31] who reported gait velocity, cadence, stride length and stride width in 898 children.

Comparison with other normative plantar pressure datasets is complicated by a lack of consensus regarding normalization and areas under the foot to be studied [46]. Multiple approaches have been reported in regards to normalization, including expressing pressure as a percentage of absolute body weight, as an absolute measure or relative to foot length. In fact only low have been found between body weight, body mass index and plantar pressure data in children, suggesting that normalization to these parameters is not supported by research.[46] In our study, children recorded highest peak pressures in the rearfoot, while adolescents, adults and older adults recorded highest peak pressures in the forefoot, these findings are supported by studies investigating foot function in children [28, 32-34] and in adults [27, 28, 47]. Our finding of comparable plantar pressures between boys and girls under 10 years is consistent with the literature [46, 48, 49]. The important finding of higher peak pressures in older adults was first reported in a study of 104 healthy individuals [28], this is supported by our study, and may explain the high prevalence of foot pain in older adults [50]. Higher pressures in older adults may be explained by ageing effects on the mechanical properties of the ankle/foot. With advancing age, foot posture becomes more pronated, palmar soft tissue stiffness increases, plantar fascia thickness increases, while ankle joint ROM and strength decrease [51]. These changes can reduce the ability of the ankle and foot to respond to repetitive stress and affect force attenuation [52]. Specifically, decreased dorsiflexion ROM has been shown to be associated with increased forefoot peak pressure [53, 54]. We suggest that significantly higher peak pressures in older adults could be attributed to age related changes associated with ankle ROM and changes in plantar soft tissue characteristics.

There are limitations to this study. First, random population sampling techniques were not employed and the exclusion criteria of conditions affecting physical performance may have resulted in a population that were particularly physically capable for their age (“healthyvolunteer effect”). Second, while pressure and force values collected with the Emed®-AT/2 were consistent with the Emed®-X in 10 adults, and in 10 children when transforming Emed®-X data to the equivalent sensor resolution of the Emed®-AT/2, our data might not be generalizable to young children with very small feet requiring higher sensor number or in faster walking or running conditions requiring higher sampling frequency. Third, our findings are based on cross-sectional data and cause-effect associations cannot be inferred.

This study has established a whole of life normative reference dataset of spatiotemporal and plantar pressure gait parameters and revealed changes to be expected across the lifespan. These reference values fill knowledge gaps in normative spatiotemporal and pressure parameters and might be useful for clinicians and researchers to compare with pathological populations. This study has explored relationships between clinical tests such as ankle ROM and strength, providing insight into factors that could potentially contribute to gait dysfunction and abnormal pressure loading patterns of people of all ages. These data provide a framework to measure the efficacy of interventions targeting gait and assist in the development of responsive outcome measures for clinical trials.

Conflict of interest. The authors have no conflict of interest to disclose.

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List of Tables and Figures

Table 1. Widely reported spatiotemporal and plantar pressure variables for children, adolescents, adults and older adults.

	Aged 3-9		Aged 10-19		Aged 20-59		Aged 60+	
	Male	Female	Male	Female	Male	Female	Male	Female
Spatiotemporal parameters								
Gait velocity (cm/s)	119.6 (21.0)	122.0 (20.5)	135.4 (16.7)	134.2 (14.3)	130.9 (15.0)	133.1 (14.6)	119.7 (17.5)	117.1 (21.8)
Stride length (cm)	99.5 (18.4)	99.9 (18.9)	141.8 (13.7)	134.4 (12.2)*	140.0 (13.3)	134.7 (11.8)*	129.0 (15.6)	120.7 (15.0)*
Stride width (cm)	7.2 (2.6)	7.0 (2.5)	7.7 (2.5)	7.2 (2.5)	9.0 (2.7)	8.1 (2.6)*	8.8 (3.0)	7.3 (92.9)*
Cadence (steps/min)	145.9 (18.8)	149.9 (26.0)	115.5 (10.4)	120.6 (8.0)*	112.5 (8.0)	119.4 (7.7)*	111.9 (9.8)	116.4 (11.5)*
Double support time (%GC)	18.1 (2.4)	18.7 (3.2)	20.6 (2.9)	20.5 (3.0)	23.3 (2.5)	22.0 (2.4)*	24.6 (3.6)	24.2 (3.7)
Maximum mean pressure (kPa)								
Rearfoot	67.0 (34.3)	76.1 (31.0)	99.2 (25.5)	102.1 (28.2)	105.6 (24.2)	99.5 (26.8)*	106.3 (37.4)	99.1 (32.1)
Midfoot	11.4 (8.8)	13.1 (12.0)	20.7 (14.6)	16.2 (12.6)*	26.2 (17.3)	22.0 (15.6)*	23.3 (22.0)	24.8 (17.9)
Forefoot	79.1 (35.3)	84.0 (30.0)	147.7 (51.0)	147.9 (40.5)	181.7 (55.8)	180.3 (45.7)	207.4 (73.9)	201.5 (74.0)
Whole foot	94.5 (4.9)	99.3 (31.9)	154.8 (49.1)	154.1 (38.1)	182.8 (55.2)	181.5 (44.7)	210.1 (73.0)	203.8 (72.5)
Peak pressure (kPa)								
Rearfoot	249.3 (129.3)	269.6 (120.1)	365.4 (129.2)	341.0 (92.3)	375.0 (122.6)	345.7 (113.5)*	356.7 (148.3)	319.9 (113.7)*
Midfoot	49.3 (26.9)	49.1 (34.0)	71.3 (41.1)	57.1 (35.5)*	80.6 (44.3)	74.4 (46.7)	75.9 (63.3)	84.7 (52.7)
Forefoot	230.0 (80.0)	245.1 (87.0)	433.4 (161.4)	431.0 (116.2)	523.9 (164.8)	527.7 (148.3)	576.1 (200.0)	570.3 (190.1)
Whole foot	290.9 (124.0)	310.8(120.3)	475.8 (163.9)	456.1 (111.9)	540.7 (168.0)	541.7 (147.0)	591.8 (203.5)	580.2 (186.4)
Pressure-time integral [(kPa)*s]								
Rearfoot	57.9 (30.1)	64.3 (29.0)	87.9 (29.3)	84.9 (25.2)	93.8 (23.3)	85.2 (24.5)*	101.7 (36.7)	93.0 (31.5)*
Midfoot	11.4 (7.9)	12.1 (10.2)	18.2 (11.7)	13.8 (9.9)*	23.2 (15.2)	19.0 (13.2)*	22.9 (20.9)	25.0 (18.3)
Forefoot	79.5 (41.9)	79.1 (36.9)	139.9 (50.8)	132.3 (42.9)	171.3 (52.4)	158.0 (41.0)*	219.9 (89.8)	214.6 (112.5)
Whole foot	120.7 (48.6)	126.2 (49.1)	203.4 (59.6)	192.1 (46.9)	232.9 (55.9)	215.5 (46.6)*	276.7 (93.9)	267.3 (111.0)
Maximum force (N)								
Rearfoot	171.2 (69.5)	179.4 (68.0)	438.6 (116.7)	391.8 (76.2)*	555.7 (104.5)	439.9 (85.6)*	496.4 (106.7)	413.2 (87.3)*
Midfoot	21.7 (16.9)	22.8 (22.3)	53.9 (45.9)	40.6 (35.6)*	67.1 (49.1)	51.5 (42.5)*	58.1 (51.6)	61.0 (46.7)
Forefoot	227.0 (82.5)	238.0 (85.0)	613.0 (180.0)	548.6 (115.6)*	800.0 (124.2)	638.9 (112)*	765.9 (125.5)	642.9 (111.4)*
Whole foot	247.5 (86.1)	254.3 (88.5)	635.0 (179.4)	562.1 (126.2)*	822.0 (137.7)	652.3 (113.7)*	787.7 (134.8)	660.2 (113.2)*
Force-time integral (N*s)								
Rearfoot	43.8 (23.4)	46.7 (22.3)	111.4 (37.2)	99.1 (27.5)*	142.8 (34.8)	110.4 (11.7)*	147.7 (48.6)	122.8 (40.0)*
Midfoot	4.1 (3.9)	4.8 (5.5)	12.4 (12.7)	8.4 (8.4)*	17.3 (15.5)	11.7 (11.7)*	16.2 (18.0)	16.2 (15.7)
Forefoot	78.5 (39.1)	80.1 (42.6)	221.6 (78.1)	183.5 (50.3)*	290.5 (65.0)	215.4 (51.5)*	315.2 (83.5)	254.3 (70.3)*
Whole foot	126.3 (54.1)	131.7 (61.0)	345.4 (110.1)	291.0 (71.3)*	450.6 (91.4)	337.5 (74.7)*	479.1 (120.6)	393.4 (107.8)*

	Aged 3-9		Aged 10-19		Aged 20-59		Aged 60+	
	Male	Female	Male	Female	Male	Female	Male	Female
Contact area (cm^2)								
Rearfoot	20.2 (4.3)	20.3 (4.8)	36.1 (5.7)	31.2 (4.1) *	40.5 (4.6)	34.1 (3.6) *	39.2 (4.4)	34.3 (3.4) *
Midfoot	7.2 (4.0)	6.7 (4.9)	12.4 (7.1)	9.7 (5.7) *	15.0 (6.9)	11.1 (5.5) *	11.9 (7.2)	11.9 (5.5)
Forefoot	42.8 (9.5)	41.3 (9.1)	72.4 (12.5)	61.9 (8.8) *	80.0 (8.6)	66.5 (7.3) *	77.6 (10.1)	68.8 (6.4) *
Whole foot	70.2 (15.4)	68.2 (16.9)	120.8 (22.7)	103.3 (16.8) *	134.8 (16.4)	111.8 (13.4) *	128.8 (19.0)	115.0 (12.9)*
Contact time (ms)								
Rearfoot	419.2 (127.0)	447.6 (135.3)	457.3 (91.1)	442.6 (81.4)	477.6 (81.6)	455.2 (84.3) *	546.1 (167.9)	526.7 (152.8)
Midfoot	310.2 (139.9)	301.9 (166.0)	349.3 (106.8)	297.1 (136.3) *	386.0 (119.8)	337.7 (117.4) *	380.7 (199.0)	403.6 (186.6)
Forefoot	688.7 (191.3)	685.8 (194.7)	686.3 (88.7)	663.8 (95.9)	701.0 (78.2)	666.6 (76.4) *	782.0 (175.3)	774.2 (221.9)
Whole foot	762.1 (187.5)	764.7 (186.3)	795.0 (107.0)	764.8 (91.4)	803.0 (80.7)	770.0 (80.0)*	883.5 (186.6)	878.0 (225.4)

* Significant gender differences ($p<0.05$)

Figure 1: Correlogram representing the relationships between spatiotemporal and plantar pressure variables with demographic and physical characteristics of children aged 3-9 years of age. Blue represents positive correlation, red represents negative correlation, results that do not achieve statistical significance (p<.05) are crossed

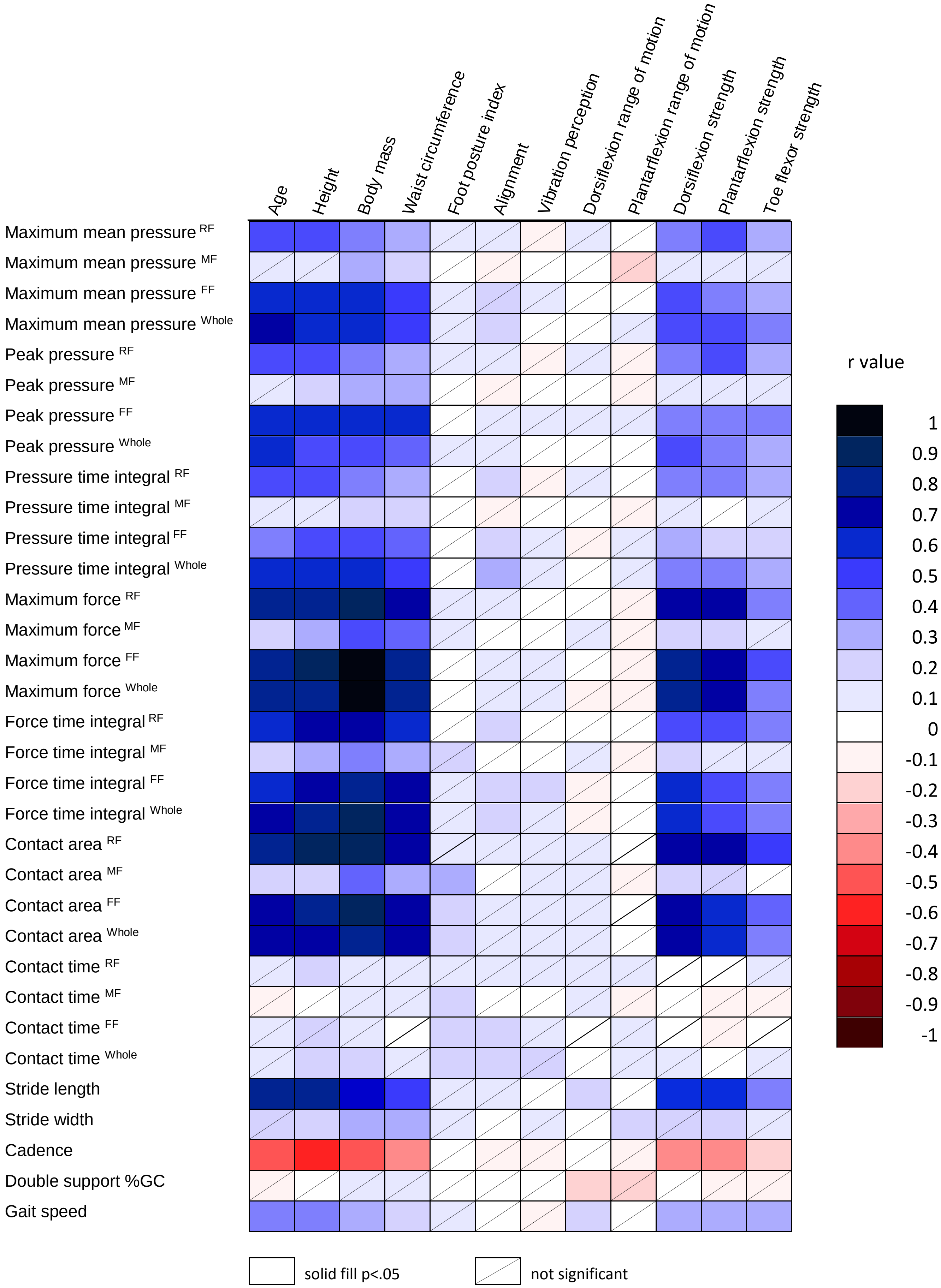


Figure 2: Correlogram representing the relationships between spatiotemporal and plantar pressure variables with demographic and physical characteristics of adolescents aged 10-19 years of age. Blue represents positive correlation, red represents negative correlation, results that do not achieve statistical significance (p<.05) are crossed

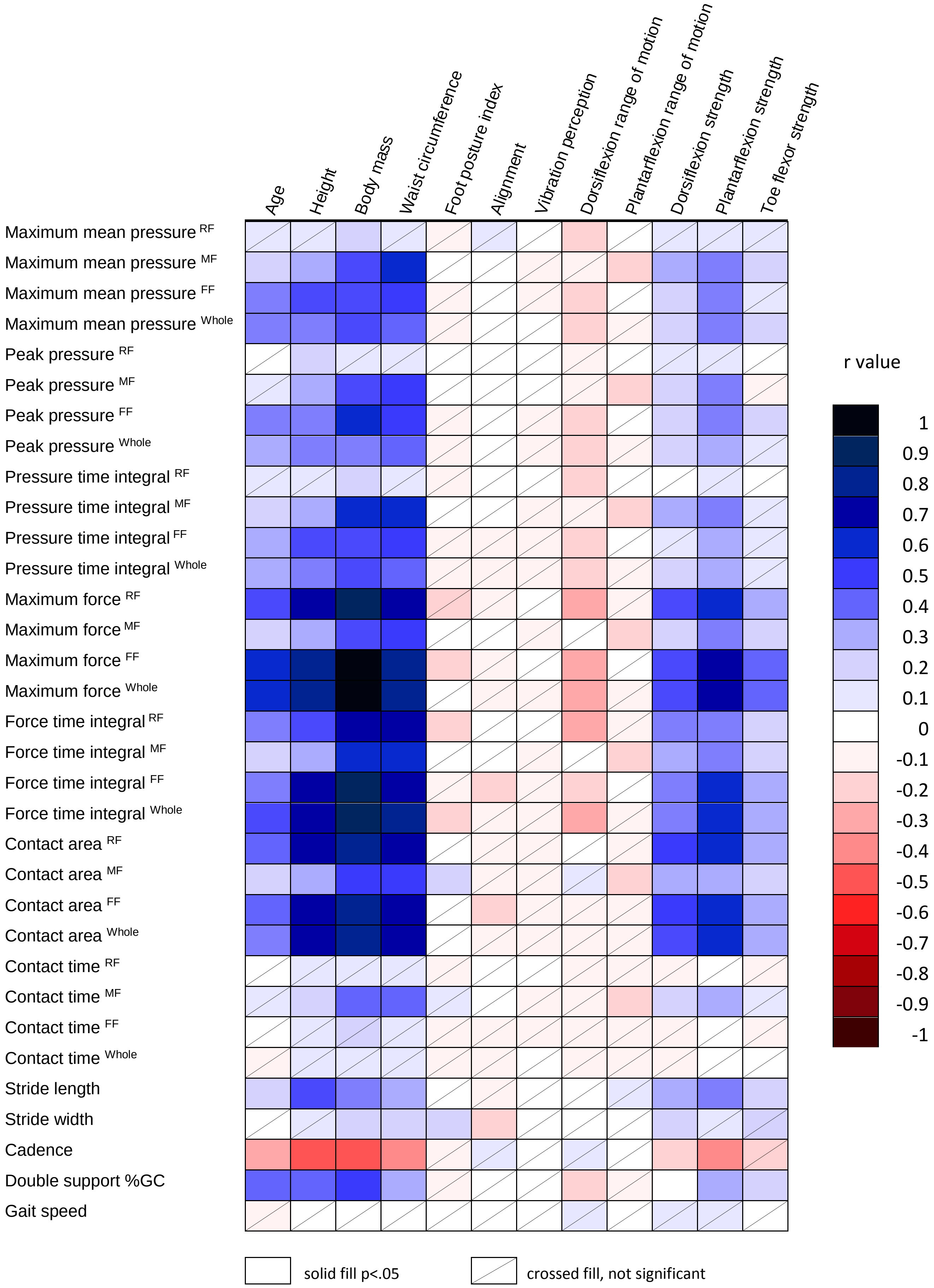


Figure 3: Correlogram representing the relationships between spatiotemporal and plantar pressure variables with demographic and physical characteristics of adults aged 20-59 years of age. Blue represents positive correlation, red represents negative correlation, results that do not achieve statistical significance (p<.05) are crossed

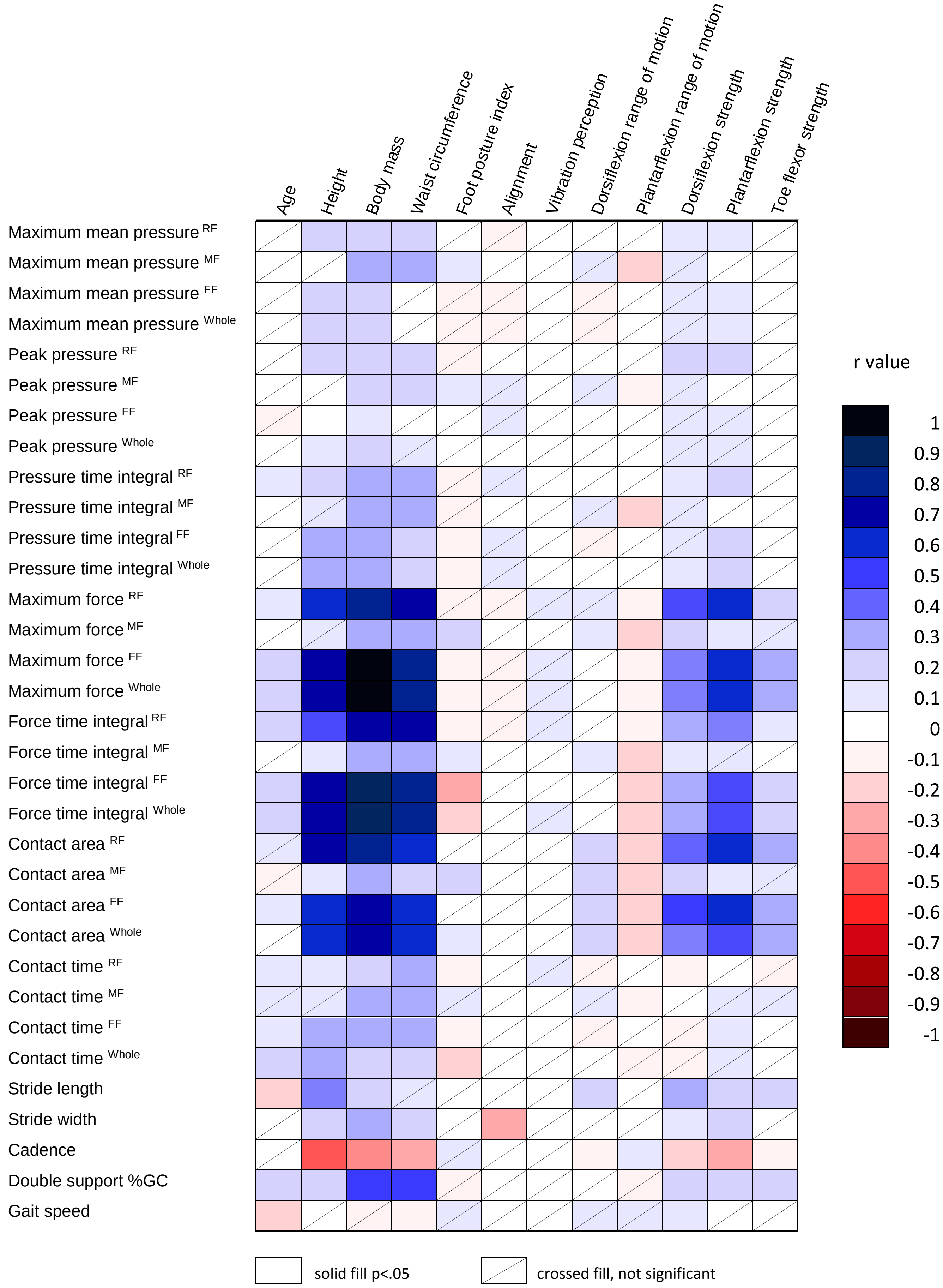
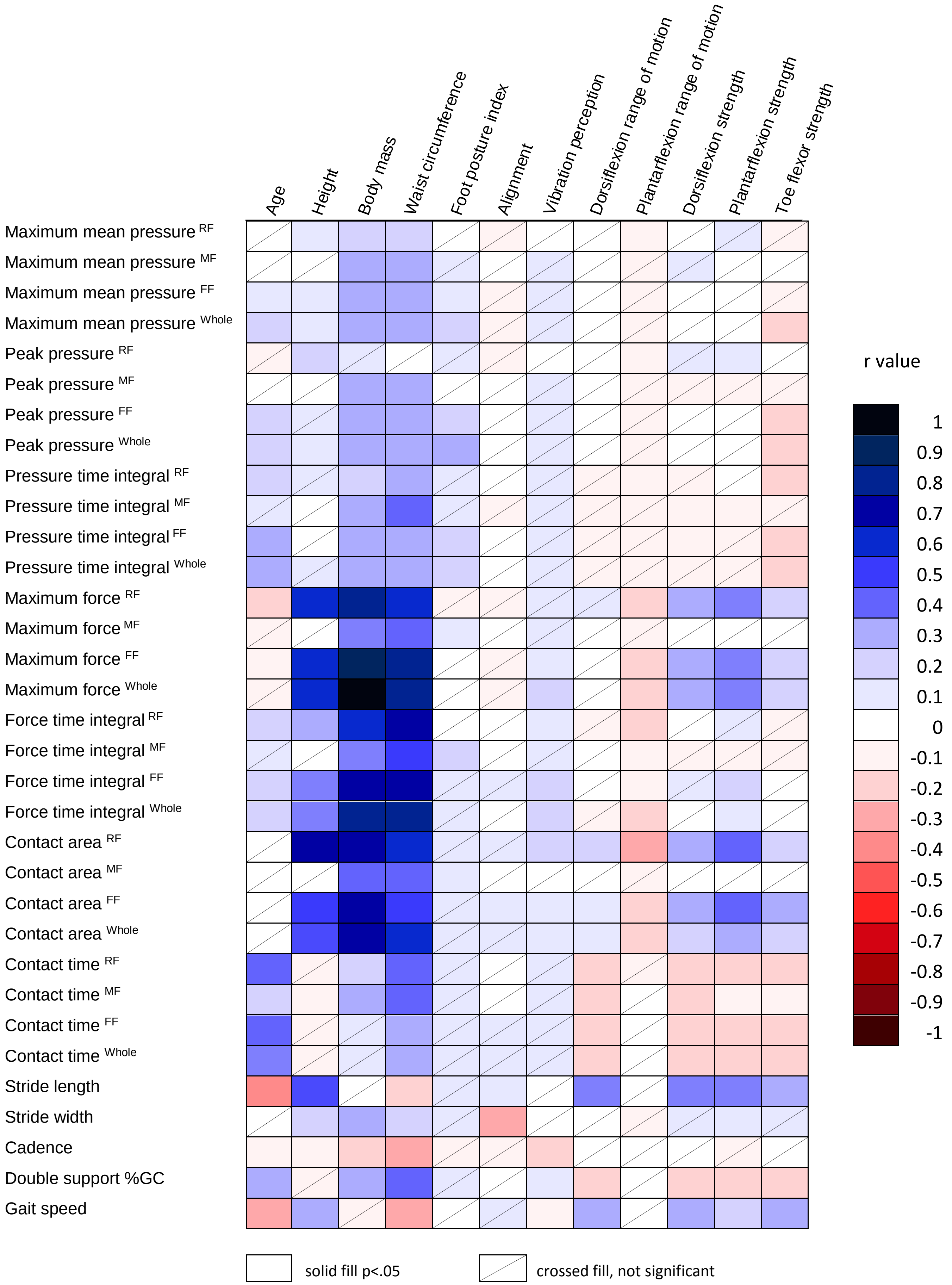


Figure 4: Correlogram representing the relationships between spatiotemporal and plantar pressure variables with demographic and physical characteristics of older adults aged 60-101 years of age. Blue represents positive correlation, red represents negative correlation, results that do not achieve statistical significance (p<.05) are crossed



Supplement 1. Definitions of spatiotemporal and plantar pressure variables

	Parameter	Definition
Spatiotemporal gait *	Step length (cm)	Distance between corresponding successive points on the heel of opposite feet measured parallel to the direction of progression for the stride
	Stride length (cm)	Distance from the heel of one foot to the following heel of the same foot
	Stride width (cm)	Distance between a line connecting two ipsilateral foot heel contacts and the contralateral foot heel contact between those events, measured perpendicular to the stride
	Cadence (steps/min)	Number of steps taken per minute
	Step time (s)	Period of time taken for one step, measured from first contact of one foot to the first contact of the other foot
	Stride time (s)	Period of time from first contact of one foot to the following first contact of the same foot
	Stance time (s)	Period of time when the foot is in contact with the ground
	Swing time (s)	Period of time when the foot is not in contact with the ground
	Single support time (s)	Period of time when only the one foot is in contact with the ground
	Double support time (s)	Period of time when both feet are in contact with the ground simultaneously during stance phase
	Stance time (%GC)	Stance time presented as a percentage of the gait cycle time (stride time)
	Swing time (%GC)	Swing time presented as a percentage of the gait cycle time
	Single support time (%GC)	Single support time presented as a percentage of gait cycle time
	Double support time (%GC)	Double support time presented as a percentage of the gait cycle time
	Gait velocity (cm/s)	Distance walked divided by ambulation time
Plantar pressure †	Maximum mean pressure (kPa)	The average of the maximum pressure values averaged for each sensor for each mask
	Peak pressure (kPa)	Mean value of the peak pressure that occurred in each sensor for each mask
	Instant of peak pressure (ms)	Average time the peak pressure occurred in each measurement
	Instant of peak pressure (%ROP)	Average time the peak pressure occurred in each measurement, measured as present of roll over phase
	Pressure-time integral [(kPa)*s]	Mean value of the pressure time integrals for each mask. The pressure-time integral corresponds to the area under the peak pressure curve.
	Mean force (N)	Average of the total mean force in each measurement for each mask.
	Maximum force (N)	Mean value of the maximum force that occurred in each sensor for each mask.
	Mean force (N)	Average of the total mean force in each measurement for each mask.
	Maximum force (N)	Mean value of the maximum force that occurred in each sensor for each mask.
	Instant of maximum force (ms)	Average time the maximum force occurred in each measurement
	Instant of maximum force (%ROP)	Average time the maximum force occurred in each measurement (measured as percent of the ROP)
	Force-time integral (N*s)	Mean value of the force time integral for each mask. The force-time integral represents the area under the force curve.
	Mean area (cm^2)	Average loaded area in each measurement for each mask
	Contact area (cm^2)	Mean value of the maximum contact areas in each mask
	Contact time (ms)	Average contact time for each mask in each sensor
	Contact time (%ROP)	Average contact time (measured in %ROP) for each mask
	Beginning of contact time (%ROP)	The average time (in % ROP) the mask begins loading
	End of contact (%ROP)	Average time (in % ROP) the mask ends loading

* ProtoKinetics movement analysis software. PKmas Users Guide http://www.protokinetics.com/images/PKMAS_Users_Guide.pdf.

† Novel scientific analysis. Manual version 24 http://www.novelusa.com/index.php?fuseaction=support.manuals

Supplement 2a.

Physical characteristics of children, adolescents, adults and older adult participants in the 1000 Norms Project

Characteristic	**Whole cohort**	**Aged 3-9**	**Aged 10-19**	**Aged 20-59**	**Aged 60+**
Height (m)	1.61 (0.2)	1.2 (0.1)	1.6 (1.3)	1.7 (0.1)	1.7 (0.1)
n	1000	140	160	400	300
Body mass (kg)	62.9 (21.1)	24.5 (7.7)	57.8 (15.2)	71.6 (14.2)	71.7 (13.7)
n	1000	140	160	400	300
Waist circumference (cm)	78.6 (15.4)	56.1 (5.9)	70.9 (9.0)	81.1 (11.2)	89.9 (12.6)
n	1000	140	160	400	300
Foot posture index	3.5 (2.4)	4.8 (1.8)	3.6 (2.3)	2.9 (2.4)	3.6 (2.3)
n	1000	140	160	400	300
Lower limb alignment (˚)	1.8 (2.7)	0.3 (3.0)	1.5 (2.5)	2.0 (2.3)	2.4 (2.7)
n	1000	140	160	400	300
Ankle dorsiflexion (˚)	30 (7.0)	32 (7.0)	31 (6.0)	31 (6.0)	29 (7.0)
n	996	136	160	400	300
Ankle plantarflexion (˚)	59 (9)	63 (8.0)	60 (8.0)	59 (9.0)	55 (7.0)
n	1000	140	160	400	300
Ankle dorsiflexor strength (N)	164.7 (61.2)	84.3 (34.0)	181.6 (50.5)	195.4 (53.8)	152.4 (46.5)
n	999	140	160	399	300
Ankle plantarflexor strength (N)	257.0 (85.6)	147.2 (49.2)	285.5 (69.0)	290.6 (78.9)	248.8 (69.5)
n	993	140	160	394	299
Toe flexor strength (n)	3 (2.4)	1.0 (1.6)	4.2 (2.0)	4.4 (2.1)	2.8 (2.4)
n	1000	1000	159	400	300
Sensation, no. *normal*	908	139	160	397	213
n	1000	140	160	400	300

Supplement 2b Sociodemographic characteristics of 1000 Norms Project sample compared to the Australian population.

Characteristic			**1000 norms project**	**Australian population**
Age (y)	Median (IQR)	Males	39.5 (16-66)	36.5[1]
		Females	39.5 (16-64)	38.3[1]
Gender %(n)	Female		50 (500)	50.2[1]
Ethnicity %(n)	British/European		74.4 (744)	68.1[2]
	Aboriginal/Torres Strait Islander		1.5 (15)	3.0[3]
	Other (Asian/American/African)		24.1 (241)	data not available
Country of birth %(n)	Australia		67.8 (678)	71.8*[4]
Socioeconomic status^	Median (IQR)		84.0 (60-96)	50 (25-75) *
BMI (mean (SD) kg/m^2)	3-17 years+	Males	18.6	19.1[5]
		Females	18.8	19.2[5]
	18+ years	Males	25.4 (3.4)	27.8*[5]
		Females	24.3 (4.0)	27.2*[5]

^Percentile rank for Index of Relative Socioeconomic Advantage and Disadvantage.
#Australian statistics reported for 15-64 year olds.
+Australian statistics reported for 2-17 year olds.
*statistically significant difference between 1000 Norms sample and Australian population, p<.05

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3. Australian Bureau of Statistics. Estimates and projections, Aboriginal and Torres Strait Islander Australians, 2001 to 2026. ABS cat. no. 3238.0. Canberra, Australia 2014.
4. Australian Bureau of Statistics. Migration, Australia, 2013–14. ABS cat. no. 3412.0. . Canberra, Australia.2015.
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Supplement 3a. Non-normalized spatiotemporal gait parameters of 1000 people aged 3-101 years per decade of life

	Entire sample	Aged 3-9		Aged 10-19		Aged 20-29		Aged 30-39		Aged 40-49		Aged 50-59		Aged 60-69		Aged 70-79		Aged 80+	
		Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Gait velocity (cm/s)	126.8 (18.9)	119.6 (21.0)	122.0 (20.5)	135.4 (16.7)	134.2 (14.3)	133.5 (14.5)	137.1 (14.5)	131.2 (12.8)	131.4 (14.2)	133.5 (16.7)	133.8 (14.7)	125.2 (14.8)	130.3 (14.5)	123.8 (13.1)	124.4 (17.1)	124.7 (17.3)	117.3 (22.7)	110.5 (20.9)	109.5 (23.0)
Step length (cm)	64.7 (9.8)	50.2 (9.4)	50.4 (9.5)	71.4 (7.0)	67.8 (6.2)	71.6 (6.2)	69.2 (5.6)	70.8 (5.6)	66.6 (5.4)	72.1 (7.1)	67.9 (5.7)	67.6 (7.1)	66.7 (5.9)	67.1 (6.3)	63.4 (6.0)	66.8 (6.5)	61.6 (7.0)	61.0 (9.1)	57.3 (8.1)
Stride length (cm)	128.4 (19.6)	99.5 (18.4)	99.9 (18.9)	141.8 (13.7)	134. (12.2)	142.2 (12.4)	137.5 (11.0)	140.8 (12.4)	132.4 (11.0)	143.4 (14.3)	134.9 (11.9)	134.7 (14.3)	132.8 (12.1)	133.3 (12.2)	126.3 (12.2)	132.3 (12.4)	122.3 (13.6)	121.3 (18.0)	113.6 (16.3)
Stride width (cm)	7.9 (2.7)	7.2 (2.6)	7.0 (2.5)	7.7 (2.5)	7.2 (2.5)	8.9 (2.8)	7.9 (2.4)	9.1 (3.1)	8.7 (2.9)	8.8 (2.5)	8.0 (2.4)	8.6 (2.5)	7.4 (2.3)	9.5 (2.7)	7.3 (2.8)	8.0 (2.9)	6.8 (2.3)	8.6 (3.3)	7.7 (3.2)
Cadence (steps/min)	120.2 (16.7)	145.9 (18.8)	149.9 (26.0)	115.5 (10.4)	120.6 (8.0)	113.3 (8.4)	120.5 (7.8)	112.4 (8.1)	119.5 (7.5)	112.1 (8.1)	119.6 (7.9)	112.2 (7.6)	118.2 (7.9)	112.3 (7.9)	118.4 (9.7)	114.0 (10.3)	115.5 (12.4)	109.5 (10.7)	115.4 (12.2)
Step time (s)	0.51 (0.07)	0.41 (0.07)	0.42 (0.07)	0.53 (0.05)	0.51 (0.04)	0.53 (0.05)	0.50 (0.03)	0.55 (0.05)	0.51 (0.03)	0.54 (0.05)	0.51 (0.04)	0.54 (0.05)	0.51 (0.04)	0.54 (0.05)	0.51 (0.04)	0.54 (0.05)	0.52 (0.05)	0.56 (0.07)	0.53 (0.05)
Stride time (s)	1.02 (0.12)	0.84 (0.11)	0.83 (0.14)	1.06 (0.10)	1.01 (0.07)	1.07 (0.08)	1.00 (0.06)	1.08 (0.07)	1.02 (0.07)	1.07 (0.08	1.00 (0.07)	1.08 (0.08)	1.01 (0.09)	1.08 (0.09)	1.01 (0.09)	1.08 (0.10)	1.04 (0.09)	1.10 (0.10)	1.06 (0.11)
Stance time (s)	0.61 (0.09)	0.49 (0.07)	0.49 (0.08)	0.62 (0.07)	0.60 (0.05)	0.65 (0.06)	0.60 (0.04)	0.66 (0.09)	0.61 (0.05)	0.65 (0.06)	0.60 (0.06)	0.67 (0.06)	0.62 (0.07)	0.66 (0.07)	0.62 (0.07)	0.67 (0.07)	0.64 (0.08)	0.69 (0.1)	0.67 (0.09)
Swing time (s)	0.40 (0.05)	0.35 (0.05)	0.34 (0.06)	0.42 (0.04)	0.40 (0.01)	0.4 (0.04)	0.40 (0.01)	0.41 (0.03)	0.40 (0.02)	0.41 (0.03)	0.40 (0.01)	0.41 (0.03)	0.40 (0.03)	0.41 (0.04)	0.40 (0.03)	0.41 (0.04)	0.40 (0.03)	0.41 (0.04)	0.39 (0.02)
Single support time (s)	0.40 (0.04)	0.35 (0.05)	0.34 (0.05)	0.41 (0.04)	0.40 (0.01)	0.41 (0.04)	0.40 (0.01)	0.40 (0.02)	0.40 (0.02)	0.40 (0.03)	0.40 (0.01)	0.41 (0.03)	0.40 (0.02)	0.41 (0.03)	0.40 (0.03)	0.41 (0.03)	0.40 (0.03)	0.41 (0.04)	0.39 (0.03)
Double support time (s)	0.23 (0.07)	0.15 (0.05)	0.15 (0.06)	0.22 (0.05)	0.21 (0.05)	0.24 (0.05)	0.21 (0.04)	0.25 (0.05)	0.22 (0.04)	0.26 (0.05)	0.22 (0.05)	0.26 (0.05)	0.23 (0.04)	0.25 (0.05)	0.23 (0.05)	0.26 (0.05)	0.25 (0.05)	0.29 (0.09)	0.28 (0.07
Stance time (%GC)	60.8 (2.0)	58.8 (1.3)	59.2 (1.7)	60.1 (1.5)	59.9 (1.6)	61.0 (1.5)	60.3 (1.6)	60.9 (2.4)	60.8 (1.4)	61.5 (1.3)	60.5 (1.2)	61.6 (1.4)	61.3 (1.2)	61.7 (1.4)	61.4 (1.6)	61.6 (1.7)	61.7 (1.6)	62.7 (2.4)	62.6 (2.5)
Swing time (%GC	39.2 (2.0)	41.2 (1.3)	40.8 (1.7)	39.9 (1.5)	40.1 (1.6)	39.0 (1.5)	39.7 (1.6)	39.1 (2.4)	39.2 (1.4)	38.5 (1.3)	39.5 (1.2)	38.4 (1.4)	38.7 (1.2)	38.3 (1.4)	38.7 (1.6)	38.4 (1.7)	38.2 (1.7)	37.3 (2.4)	37.4 (2.5)
Single support time (%GC)	38.7 (1.9)	40.9 (1.2)	40.6 (1.7)	39.6 (1.6)	39.5 (1.8)	38.5 (1.5)	39.2 (1.3)	38.3 (1.1)	38.9 (1.4)	37.9 (1.6)	39.0 (1.0)	38.0 (1.4)	38.4 (1.1)	37.8 (1.5)	38.6 (1.6)	37.7 (1.4)	37.9 (1.6)	37.0 (2.4)	37.0 (2.3)
Double support time (%GC)	22.2 (3.6)	18.1 (2.4)	18.7 (3.2)	20.6 (2.9)	20.5 (3.0)	22.5 (2.7)	21.3 (2.4)	23.2 (2.1)	22.0 (2.7)	23.7 (2.6)	21.8 (2.1)	23.8 (2.6)	23.0 (2.2)	23.9 (2.6)	23.1 (1.4)	24.0 (2.7)	23.8 (3.0)	25.7 (4.8)	25.8 (4.5)

Mean (SD), %GC= percentage of gait cycle time

Supplement 3b. Normalized spatiotemporal gait parameters of 1000 people aged 3-101 years per decade of life (unit: centimetres)

	Entire sample	Aged 3-9		Aged 10-19		Aged 20-29		Aged 30-39		Aged 40-49		Aged 50-59		Aged 60-69		Aged 70-79		Aged 80+	
		Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Gait velocity (cm/s)	44.4 (6.9)	49.8 (7.4)	50.6 (8.2)	46.3 (6.1)	46.6 (5.1)	44.3 (5.1)	47.7 (4.9)	43.7 (4.4)	45.5 (4.9)	44.2 (5.5)	46.0 (5.1)	41.7 (4.7)	44.9 (4.8)	41.5 (4.4)	43.0 (5.7)	41.1 (5.6)	40.5 (7.6)	37.2 (7.2)	38.2 (7.7)
Step length (cm)	77.6 (9.1)	85.2 (8.8)	84.2 (11.0)	82.1 (8.9)	80.5 (6.9)	77.7 (6.6)	82.4 (6.4)	76.9 (5.2)	78.8 (6.1)	77.8 (7.8)	78.7 (6.6)	73.7 (6.4)	77.9 (5.9)	74.0 (7.3)	74.6 (6.7)	72.4 (6.4)	72.3 (7.5)	67.9 (10.9)	69.0 (8.9)
Stride length (cm)	153.6 (17.8)	168.5 (16.3)	166.6 (20.9)	162.5 (16.3)	158.9 (13.7)	153.5 (13.9)	163.5 (12.5)	153.0 (12.0)	156.1 (12.0)	154.3 (16.4)	156.4 (13.5)	146.4 (12.4)	154.3 (12.1)	146.9 (13.6)	148.0 (13.0)	143.3 (11.9)	142.7 (14.3)	134.6 (20.9)	135.7 (18.7)
Stride width (cm)	9.8 (3.6)	12.4 (4.8)	12.1 (4.7)	9.1 (3.0)	8.8 (3.0)	9.7 (3.1)	9.5 (2.8)	10.2 (3.5)	10.2 (3.5)	9.8 (2.7)	9.5 (3.0)	9.5 (2.7)	8.8 (2.8)	10.6 (3.0)	8.6 (3.3)	8.8 (3.3)	8.0 (2.9)	9.7 (3.9)	9.3 (3.9)
Cadence (steps/min)	0.58 (0.06)	0.59 (0.08)	0.61 (0.09)	0.57 (0.05)	.60 (0.04)	0.58 (0.04)	0.60 (0.04)	0.58 (0.05)	0.59 (0.04)	0.58 (0.52)	0.59 (0.04)	0.58 (0.05)	0.59 (0.04)	0.57 (0.06)	0.59 (0.05)	0.58 (0.07)	0.56 (0.07)	0.55 (0.06)	0.57 (0.07)
Step time (s)	1.76 (0.15)	1.73 (0.21)	1.69 (0.20)	1.78 (0.16)	1.73 (0.10)	1.76 (0.11)	1.75 (0.10)	1.78 (0.98)	1.73 (0.10)	1.76 (0.13)	1.72 (0.11)	1.77 (0.11)	1.73 (0.12)	1.79 (0.13)	1.74 (0.13)	1.77 (0.16)	1.77 (0.15)	1.86 (0.19)	1.81 (0.17)
Stride time (s)	3.49 (0.29)	3.45 (0.40)	3.35 (0.41)	3.54 (0.27)	3.43 (0.19)	3.48 (0.23)	3.44 (0.21)	3.52 (0.19)	3.44 (0.21)	3.51 (0.26)	3.43 (0.22)	3.53 (0.22)	3.45 (0.21)	3.56 (0.26)	3.46 (0.26)	3.49 (0.32)	3.52 (0.29)	3.67 (0.37)	3.62 (0.37)
Stance time (s)	2.11 (0.22)	2.01 (0.25)	1.97 (0.25)	2.10 (0..18)	2.03 (0.15)	2.11 (0.16)	2.04 (0.14)	2.14 (0.22)	2.10 (0.15)	2.14 (0.16)	2.06 (0.17)	2.15 (0.17)	2.09 (0.16)	2.19 (0.19)	2.10 (0.26)	2.14 (0.21)	2.17 (0.23)	2.28 (0.29)	2.26 (0.30)
Swing time (s)	1.36 (0.11)	1.42 (0.16)	1.37 (0.15)	1.42 (0.14)	1.37 (0.06)	1.36 (0.08)	1.36 (0.08)	1.36 (0.08)	1.34 (0.07)	1.36 (0.11)	1.35 (0.08)	1.34 (0.08)	1.34 (0.07)	1.36 (0.11)	1.33 (0.09)	1.35 (0.12)	1.34 (0.10)	1.36 (0.13)	1.34 (0.11)
Single support time (s)	1.36 (0.11)	1.43 (0.16)	1.37 (0.15)	1.41 (0.10)	1.37 (0.06)	1.36 (0.10)	1.36 (0.10)	1.36 (0.08)	1.34 (0.07)	1.35 (0.11)	1.34 (0.79)	1.35 (0.07)	1.34 (0.07)	1.36 (0.10)	1.33 (0.09)	1.32 (0.11)	1.35 (0.11)	1.36 (0.11)	1.35 (0.13)
Double support time (s)	0.78 (0.17)	0.63 (0.13)	0.62 (0.14)	0.72 (0.13)	0.71 (0.13)	0.76 (0.12)	0.73 (0.11)	0.82 (0.10)	0.76 (0.12)	0.84 (0.12)	0.75 (0.11)	0.84 (0.12)	0.80 (0.11)	0.86 (0.13)	0.80 (0.15)	0.84 (0.15)	0.83 (0.16)	0.95 (0.27)	0.94 (0.23)

Mean (SD) Normalized to leg length measured from anterior superior iliac spine to medial malleolus