Acta of Bioengineering and Biomechanics
Vol. 14, No. 3, 2012

Original paper
DOI: 10.5277/abb120302

Three-dimensional human gait pattern – reference data for normal men

BOGDAN PIETRASZEWSKI*, SŁAWOMIR WINIARSKI, SEBASTIAN JAROSZCZUK

Department of Biomechanics, University School of Physical Education, Wrocław, Poland.

The aim of this research was to establish a kinematic pattern of adult gait for motion analysis system BTS Smart-E used in the research conducted in the Laboratory of Biomechanical Analysis, University School of Physical Education, Wrocław. This research presents the results of gait patterns for a group of 17 adult males for three speed levels: high (1), preferred (2), and low (3). Subject's sex, age and speed of gait are to be considered in the kinematic normal gait pattern. No statistically significant differences were observed between the right and the left limb. However, differences between the high, preferred and low gait speed were noticeable. An increase in gait speed was related to the change in the angular range of motion in the hip, knee and ankle joints sagittal plane. The range of motion in joints mostly increased with the subjects' speed. No significant differences between the range of motion and speed were observed in the ankle joint.

Key words: *motion analysis, gait, normal pattern, kinematics, variability*

1. Introduction

Human gait is the basic form of human locomotion and the most comfortable and economical way of movement at short distances [1], [2]. Despite complex, neural control, the gait is characterised by smooth and repeatable movements in human joints, which can be recorded by cinematographic methods. In the clinical applications, gait stereotype is frequently used in human motion analysis to compare the results obtained with those of a reference group. Unfortunately, the results of the reference group provided by the software producers are based on small research groups (e.g., norms established on few subjects) or the research is conducted in non-laboratory conditions. Few published studies assess also the variability of kinematic measures.

Normative gait data are also essential for diagnosing and treatment of abnormal gait patterns. KADABA et al. [3] studied repeatability of gait variables for kinematic, kinetic, and electromyographic data and spatiotemporal parameters of 40 normal subjects. Their results suggest that with the subjects walking at their natural or preferred speed, the gait variables are quite repeatable. Similar conclusion was reached by GROWNEY et al. [4], who studied lower extremity kinematic and kinetic profiles obtained from 5 adult subjects for hip, knee and ankle joints in all planes. ÖBERG et al. [5] measured basic, spatio-temporal gait parameters in 233 healthy subjects (116 men and 117 women) from 10 to 79 years of age and basic joint angle parameters for the same experimental group [6]. The results of their work are presented in a series of reference tables for slow, normal, and fast gait. AL-OBAIDI et al. [7] studied spatio-temporal gait parameters of healthy young adults, 20 to 29 years of age, from both genders from Kuwait and Sweden and found several significant differences between Kuwaiti and Swedish subjects in their manner of walking.

* Corresponding author: Bogdan Pietraszewski, Biomechanics Department, University School of Physical Education, Paderewskiego 35, 51-612 Wrocław, Poland. Tel.: +48 71 3473306, fax: +48 71 3473063, e-mail: bogdan.pietraszewski@awf.wroc.pl

Received: March 30th, 2011
Accepted for publication: May 4th, 2012

CHESTER et al. identified age-related differences in kinematic and kinetic gait parameters in children aged 3–13 years [8] and in adults [9] and pointed to the importance of using age-matched normative data to discriminate between paediatric age groups for clinical gait analysis. STANSFIELD et al. [10] studied 26 healthy 7-year-old children to check the importance of age or speed in the characterization of joint angles, moments, and powers. From their study they concluded that the kinematics and kinetics are characterized mainly by normalized speed of progression and not age. The clinical importance of these results is that normalized speed of walking, rather than age, should be considered when comparing normal gait with pathologic one. WU and MILLON [11] measured the kinematics and dynamics at the lower extremity joints during a Tai Chi gait and compared the results to those of normal walking gait. MACWILLIAMS et al. [12] provided kinematic and kinetic databases for normal gait for foot joint angles, moments and powers during adolescent gait using multi-segment foot model.

Several projects were devoted to analysis of gait of different age groups. OSTROSKY et al. [13] described active range of motion during self-selected gait speed in younger and older people. They found the gait of older people to differ significantly from the walking pattern of young people for selected variables. Older people demonstrate less knee extension and a shorter stride length compared with younger people. CHEN et al. [14] studied the gait of gender-matched groups of 24 young and 24 old healthy adults during a 4 m walk and compared the results to adults while stepping over obstacles of 0, 25, 51, or 152 mm in height.

Normal gait pattern was used, among other things, in creating the normative gait databases. GORTON et al. [15] investigated one subject's gait by 24 examiners at 12 motion analysis laboratories and observed variability of nine kinematic parameters. They assessed four sources of variability of gait data: (1) between examiners, (2) trials, (3) systems, and (4) days of evaluation using standardized gait analysis protocol. In the second part of their experiment [16] they concluded that speed is a significant influential factor for knee flexion, hip rotation and pelvic obliquity. Normative gait data were also used in comparison of two normative paediatric gait databases by CHESTER et al. [17]. Standardization has been shown to have a positive impact on gait variability.

Three-dimensional motion analysis is commonly used to determine pathologies for treatment planning, evaluation, as well as outcomes of research in children and adolescent human gait. Thus, the aim of our present research was to establish a kinematic pattern of adult gait for motion analysis system BTS Smart-E used in the research conducted in the Laboratory of Biomechanical Analysis, University School of Physical Education, Wrocław. Subject's sex, age and speed of gait are to be considered in the kinematic normal gait pattern.

This work presents the results of gait patterns for an adult male group for three speed levels: high (1), preferred (2), and low (3).

2. Materials and Methods

2.1. Research material

Seventeen (17) students of the University School of Physical Education participated in the research. All the subjects were healthy and did not have any lower limbs injuries in the past. The age of the male subjects was 22.0 ± 1.0 y.o., body mass: 76.3 ± 6.8 kg and body height: 1.79 ± 0.05 m. Detailed anthropometric measurements of the lower limbs, necessary to apply Davis model, were conducted (table 1).

Table 1. Anthropometric measurements of the lower limbs necessary for the gait model (mean value ± standard deviation)

Body height (B-v)	1795 ± 46 mm
Biiliocristale diameter (ic-ic)	258 ± 17 mm
Pelvis height right (tro-ic)	96 ± 10 mm
Pelvis height left (tro-ic)	96 ± 10 mm
Legs length right (B-tro)	936 ± 34 mm
Legs length left (B-tro)	936 ± 35 mm
Knee width right (epl-epm)	111 ± 6 mm
Knee width left (epl-epm)	111 ± 6 mm
Bimalleolare width right (mlt-mlf)	75 ± 4 mm
Bimalleolare width left (mlt-mlf)	75 ± 4 mm
Body weight	76.3 ± 6.8 kg

The subject was asked to walk the distance of ca. 10 meters with three different speeds: high (1.86 ± 0.27 m/s), preferred (1.36 ± 0.17 m/s) and low (1.16 ± 0.17 m/s). The subject was to select the speed himself.

The subjects examined expressed written consent to participate in the research. The Senate Committee for the Ethics of Scientific Research of University School of Physical Education accepted the performance of the research.

2.2. Method

BTS Smart-E (BTS Bioengineering, Milan, Italy) motion analysis system (MAS) was used to record the

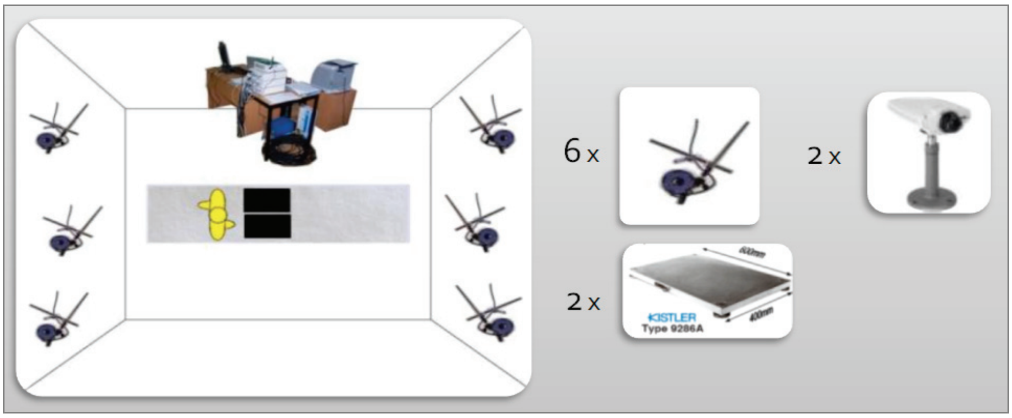

Fig. 1. The measurement set-up of the BTS Smart-E motion analysis system.
Six near-infrared cameras are mounted on the walls
and two Kistler force plates installed on a 10 m long walkway,
(see text for details)

measurements of kinematics and movement dynamics. The system contained: 6 digital infrared cameras (1.1 μm) at 120 Hz sampling frequency, two NetworkCam AXIS 210A visible range cameras at 20 Hz frequency (figure 1). All the appliances conduct the measurements simultaneously. 22 photo-reflexive markers were placed on the subject's body in accordance with the modified procedure for Helen Hayes-Davis model [18]–[20] used by the BTS MAS. A double-sided adhesive tape was used to attach the markers to the subject's body in the strictly determined spots. The data were collected by the USB/PC controller and analysed in BTS Smart Analyzer. The research posts contained: BTS Smart Capture – data collection, Smart Tracker – markers' tracking and Smart Analyzer – analysis and data processing. Data collection was synchronized by the central processing unit with video controller (VIX System) and 3 concentrators (one analogue, 32 channels Hub and two digital Ethernet Hubs containing 4 communications ports). The six IR cameras were attached to the laboratory walls.

In the experimental group, gait was recorded once for each speed (high, preferred and low) in the set of 8 repetitions, which contained from 3 to 6 gait cycles (depending on the gait speed). The first and the last gait cycles were excluded from the analysis.

The recorded raw data were then computed by the Smart Analyzer software. For each of the gait parameters mean and standard deviation were calculated and averaged over the gait cycles. Angle-time characteristics depicting the dynamic range of movement at the main subject's joints were then acquired. All graphs were averaged over cycles and expressed as percentages of the gait cycle.

All measurements were carried out in the Laboratory of Biomechanical Analysis (ISO 1374-b/3/2009, PN-EN ISO 9001:2009 certificate) of the University School of Physical Education, Wrocław.

3. Results

Table 2 represents the basic temporal and spatial parameters of the subjects' gait for n = 15 males (mean values with standard deviation). The mean gait speed for the low-speed gait was 1.16 m/s, for the preferred-speed gait 1.36 m/s and for the high-speed gait 1.86 m/s. Gait cadence was highest for the high speed of the gait (128.4 steps/min), then for the preferred speed (110.4 steps/min) and the lowest for the low speed (102.6 steps/min). The absolute stride time (cycle time) decreases with speed from 1.18 s for the low speed to 0.94 s for the high speed. The step and stride lengths increase with the speed. For the low speed the stride length is 1.35 m, for the preferred speed 1.47 m and for the high speed 1.73 m. The step length for the right and left limb for low speed was 0.58 and 0.60 m, for the preferred speed 0.61 and 0.64 m, and for the high speed 0.69 and 0.73 m, respectively. The same tendencies were noticed for both lower limbs. The width of steps is a gait parameter which is to be considered in a pathological case and does not discriminate the three test tasks.

The final speed of swing changes significantly along with the gait speed from 2.9 m/s for low speed for both limbs, through 3.28 and 3.32 m/s for preferred

Table 2. Spatio-temporal gait parameters for the experimental group for the right (R) and left (L) lower limbs expressed in absolute or relative units (mean value ± standard deviation)

Gait speed	High	Preferred	Low
gait speed [m/s]	1.86 ± 0.27	1.36 ± 0.17	1.16 ± 0.17
cadence [steps/min]	128.4 ± 8.4	110.4 ± 8.4	102.6 ± 7.2
stride length [m]	1.73 ± 0.19	1.47 ± 0.13	1.35 ± 0.13
stride width [m]	0.17 ± 0.01	0.17 ± 0.03	0.16 ± 0.02
stride time (cycle time) [s]	0.94 ± 0.06	1.09 ± 0.8	1.18 ± 0.08
Right lower limb			
final speed of swing R [m/s]	4.3 ± 0.52	3.28 ± 0.41	2.9 ± 0.35
step length R [m]	0.69 ± 0.06	0.61 ± 0.06	0.58 ± 0.07
relative stance duration R [%]	64.6 ± 1.3	65.1 ± 3.6	66.9 ± 1.4
relative swing duration R [%]	35.4 ± 1.3	33.3 ± 1.9	33.1 ± 1.4
relative dbl stance durat. R [%]	14.4 ± 1.5	16.4 ± 1.4	16.9 ± 1.7
stance duration R [s]	0.61 ± 0.04	0.71 ± 0.06	0.79 ± 0.07
swing duration R [s]	0.33 ± 0.02	0.36 ± 0.03	0.39 ± 0.02
double stance duration R [s]	0.14 ± 0.02	0.18 ± 0.02	0.20 ± 0.03
Left lower limb			
final speed of swing L [m/s]	4.26 ± 0.46	3.32 ± 0.39	2.9 ± 0.34
step length L [m]	0.73 ± 0.05	0.64 ± 0.04	0.60 ± 0.05
relative stance duration L [%]	64.9 ± 0.9	62.2 ± 1.4	66.6 ± 1.6
relative swing duration L [%]	36.0 ± 0.9	33.8 ± 1.4	33.3 ± 1.6
relative dbl stance durat. L [%]	14.4 ± 1.0	16.7 ± 2.0	16.6 ± 1.3
stance duration L [s]	0.60 ± 0.05	0.72 ± 0.06	0.78 ± 0.07
swing duration L [s]	0.34 ± 0.02	0.37 ± 0.03	0.39 ± 0.02
double stance duration L [s]	0.13 ± 0.02	0.18 ± 0.03	0.20 ± 0.02

speed up to 4.3 and 4.26 m/s for high speed for right and left limb, respectively. For the right lower limb the stance duration decreases (relative from 66.9, through 65.1 to 64.6% of gait cycle (% GC)) and the relative swing duration increases (from 33.1% to 35.4% GC) as the speed increases. The relative double stance duration decreases as speed increases from 16.9% to 14.4%. For the left lower limb similar trends have occurred.

Terminal speed of swing, stance, swing and double stance absolute durations also strongly depend on the mean speed of gait and are shown only for reference.

Figures 2 and 3 show mean, angular course of movement variability in hip, knee and ankle joints for the limbs in frontal plane (first column), sagittal plane (second column) and transversal plane (third column). In the frontal plane for the right lower limb the pelvis moved repetitively with a range of movement (ROM) being the highest, 8.5 deg, for the high speed, 6.8 deg for the preferred speed and 6.3 deg for the low speed. The hip ROM was the highest (14.9 deg) for the high speed of gait, then 12.0 deg for the preferred speed and the lowest (11.2 deg) for the low speed.

Similar behaviour was observed in the sagittal plane. The pelvis was tilted more extensively for the high speed of the gait (ROM 1.8 deg), then 1.2 deg for the preferred speed and 1.0 deg for the low speed. Small ROM in pelvic tilt manifested itself by poorly repetitive movements. The highest hip flexion ROM was noticed for the fast gait (53.3 deg), then for the preferred speed (45.5 deg) and lowest for the low speed (42.0 deg). The ROM for the knee joint was also the highest for high speed (60.7 deg) followed by 57.8 deg and 56.1 deg for the preferred and low speed of the gait. The movement in the ankle joint is nearly speed independent. The ROM for the high speed was 27.6 deg, for the preferred 27.4 and for the low speed 26.8 degrees, but the difference was not significant.

In the transversal plane pelvis rotated with the highest ROM for the high speed (18.8 deg), then for the preferred speed (14.1 deg), and for the low speed (11.7 deg). The hip rotation was the highest also for the high speed (16.0 deg), then for the preferred speed (15.1 deg), and the lowest for the low speed (14.7). Foot progression ROM does not change significantly with the gait speed. For the high speed it was 13.6 deg, for the preferred speed 13.1, and for the low speed 13.0 deg.

No significant differences between the right and left lower limbs in ROM of the analysed joints were observed (figures 2 and 3).

RIGHT

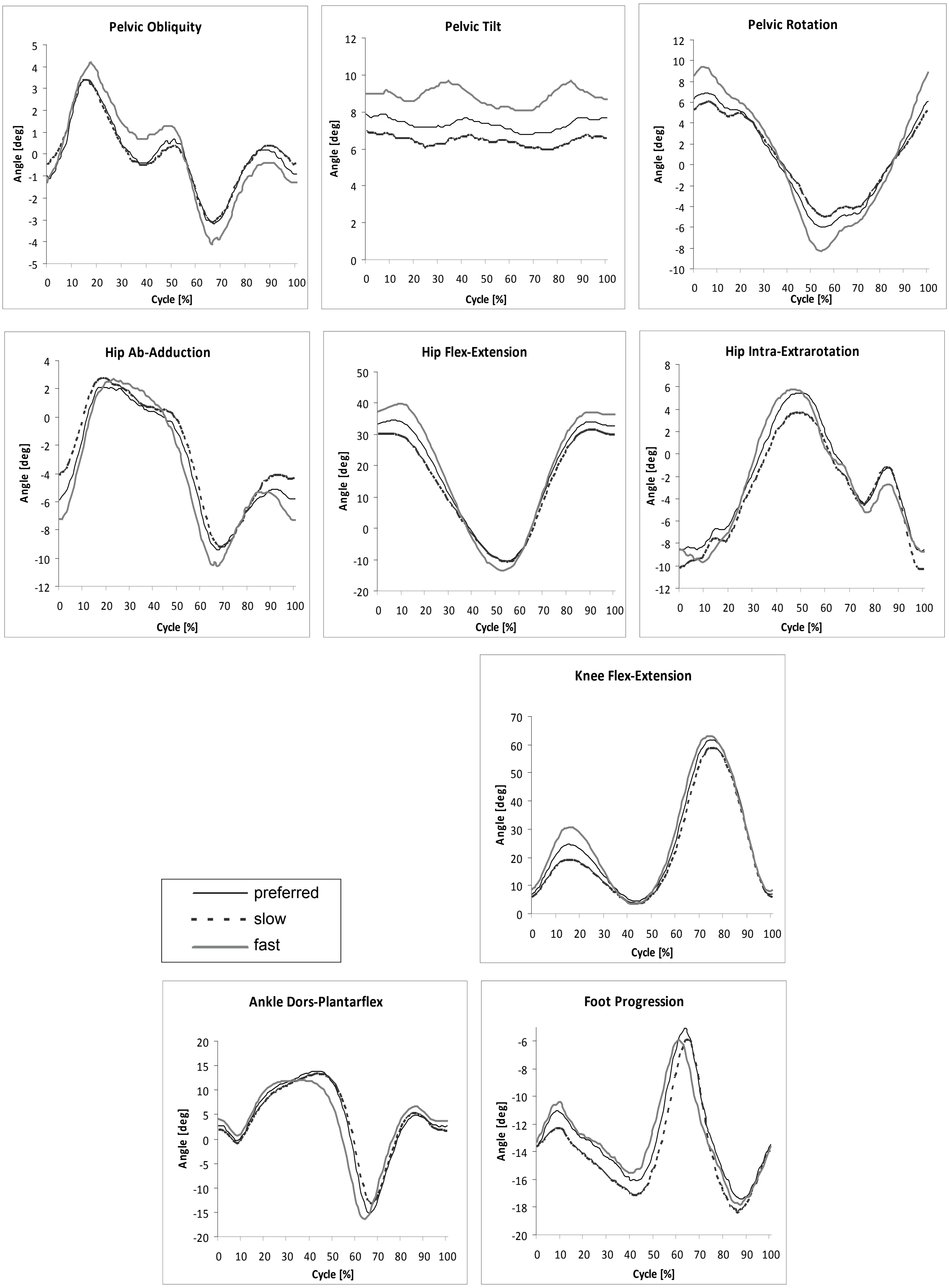

Fig. 2. Angle-time characteristics for the pelvis, hip, knee and ankle motion in the frontal, sagittal and transversal plane for the fast (grey), preferred (black) and slow (broken line) gait speed. Mean values, $N = 17$ men. Right lower limb

LEFT

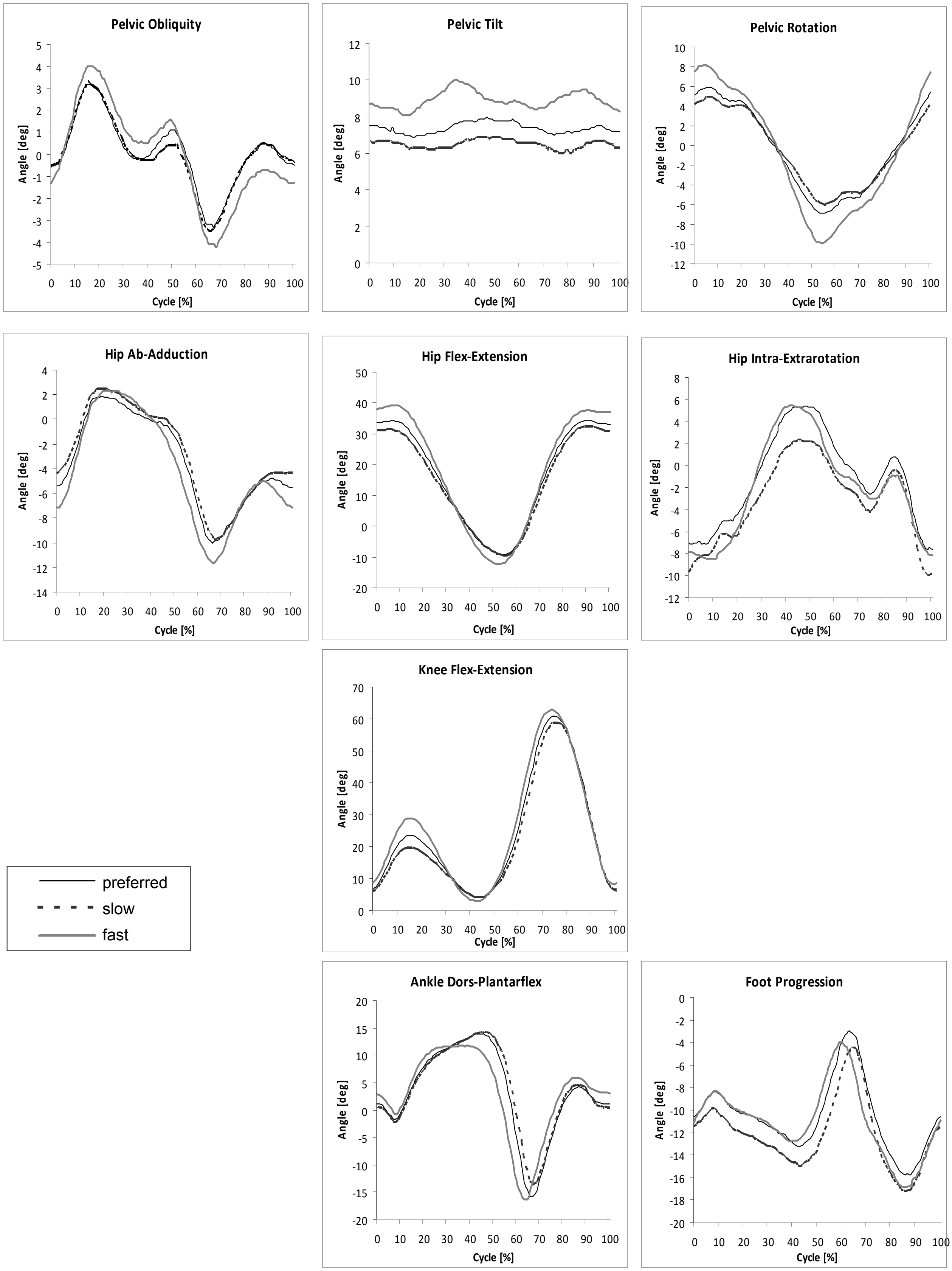

Fig. 3. Angle-time characteristics for the pelvis, hip, knee and ankle motion in the frontal, sagittal and transversal plane for the fast (grey), preferred (black) and slow (broken line) gait speed. Mean values, $N = 17$ men. Left lower limb

4. Discussion

The BTS Smart-E gait analyzer provides quantitative measurements of kinematic gait parameters. These variables can be used in study in different ways. We have chosen to present a few spatio-temporal and joint angle parameters that can be easily defined during the gait cycle. Such reference data are important in all gait analysis [21]. No statistically significant differences in these parameters were observed between the right and left lower limbs. This result agrees with the findings of KETTELKAMP et al. [22], who found no significant difference between the sexes except for knee position in mid-stance. However, the differences between the high, preferred and low gait speed were noticeable. The increase in gait speed was related to the change in the angular range of motion in the hip, knee and ankle joints sagittal plane. Similar correlations were observed in the pelvis, hip, knee and ankle joints for the face and transversal planes. The range of motion in joints increased with the subjects' speed. No significant differences in the range of motion with speed were observed in the ankle joint (27.6 deg – high, 27.4 deg – preferred and 26.8 deg – low speed) for the sagittal view.

Many measurement data can be found in the literature, however many researchers claim [23] that each laboratory, due to its specificity, should have norms adjusted to its measurement conditions. Published data do not significantly differ from those in our present study. In a statistical analysis, ÖBERG et al. [5] found a statistically significant age-variability for basic gait parameters, speed and step length at normal and fast gait, but not for step frequency. In the step length parameter there were significant interactions between age and sex at normal and fast gait. In their upcoming work, ÖBERG et al. [6] presented joint angle sagittal kinematics and found age-related changes slightly more pronounced at slow gait speed than at fast speed. Öberg's data corresponds well with our findings although the gait speed for the similar age group (20–29 years) was significantly lower than the gait speed in our study in all three test groups. The walking cadence for the fast gait was 2.34 steps/sec (140.4 steps/min), for the normal gait 1.98 steps/sec (118.8 steps/min) and for the slow gait 1.55 steps/sec (93.0 steps/min). The step length for the high speed was 71.2 m, for the preferred speed 61.6 m and for the low speed 52.7 m. They also found that joint angles increased with increasing gait speed. The increase was statistically significant ($p > 0.05$) for all angle parameters. Knee angle at mid-stance increased from about 15 deg to 24 deg, knee swing increased from about 65 deg to 68 deg, and hip flexion-extension increased from about 43 deg to 53 deg for men. The minor differences between the studies are mainly due to the mismatch in gait speeds.

To conclude, in the present study, we have presented gait-speed related reference data for basic kinematical spatio-temporal and angular parameters during human normal gait. We found major changes with increasing gait speed and no differences between left and right sides. The tables presented can be used as normative data for nondisabled male subjects.

References

[1] BOBER T., *Biomechanika chodu i biegu*, Studia i materiały AWF we Wrocławiu, Wrocław, 1985.

[2] WINTER D.A., *Biomechanics and Motor Control of Human Movement*, J. Wiley & Sons, Hoboken, N.J., 2005.

[3] KADABA M., RAMAKRISHNAN H., WOOTTEN M., GAINEY J., GORTON G., COCHRAN G., *Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait*, J. Orthop. Res., 1989, 7(6), 849–860.

[4] GROWNEY E., MEGLAN D., JOHNSON M., CAHALAN T., AN K., *Repeated measures of adult normal walking using a video tracking system*, Gait Posture, 1997, 6(2), 147–162.

[5] ÖBERG T., KARSZNIA A., ÖBERG K., *Basic gait parameters: Reference data for normal subjects 10–79 years of age*, J. Rehabil. Res. Dev., 1993, 30, 210–233.

[6] ÖBERG T., KARSZNIA A., ÖBERG K., *Joint angle parameters in gait. Reference data for normal subjects 10-79 years of age*, J. Rehabil. Res. Dev., 1994, 31, 199–213.

[7] AL-OBAIDI S., WALL J.C., AL-YAQOUB A., AL-GHANIM M., *Basic gait parameters: a comparison of reference data for normal subjects 20 to 29 years of age from Kuwait and Scandinavia*, J. Rehab. Res. & Develop., 2004, 40(4), 361–366.

[8] CHESTER V.L., TINGLEY M., BIDEN E.N., *A comparison of kinetic gait parameters for 3–13 year olds*, Clin. Biomech., (Bristol, Avon), 2006, 21(7), 726–32. doi:10.1016/j.clinbiomech.2006.02.007.

[9] CHESTER V.L, WRIGLEY A.T., *The identification of age-related differences in kinetic gait parameters using principal component analysis*, Clin. Biomech., (Bristol, Avon), 2008, 23(2), 212–220. doi:10.1016/j.clinbiomech.2007.09.007

[10] STANSFIELD B.W., HILLMAN S.J., HAZLEWOOD M.E., LAWSON A.A., MANN A.M., LOUDON I.R., ROBB J.E., *Sagittal Joint Kinematics, Moments, and Powers Are Predominantly Characterized by Speed of Progression not age, in normal children*, J. Pediatr. Orthop., 2001, 21(3), 403–411.

[11] WU G., MILLON D., *Joint kinetics during Tai Chi gait and normal walking gait in young and elderly Tai Chi Chuan practitioners*, Clin. Biomech., (Bristol, Avon), 2008, 23(6), 787–795. doi:10.1016/j.clinbiomech.2008.02.001

[12] MACWILLIAMS B., COWLEY M., NICHOLSON D., *Foot kinematics and kinetics during adolescent gait*, Gait Posture, 2003, 17(3), 214–224.

[13] OSTROSKY K.M., VANSWEARINGEN J.M., BURDETT R.G., GEE Z., *A comparison of gait characteristics in young and old subjects*, 1994, 74(7), 637–644.

[14] CHEN H.C., ASHTON-MILLER J.A., ALEXANDER N.B., SCHULTZ A.B., *Stepping over obstacles: gait patterns of healthy young and old adults*, J. Gerontol., 1991, 46(6), M196–203.

[15] GORTON G., HEBERT D., GOODE B., *Assessment of the kinematic variability between 12 Shriner's motion analysis laboratories*. Part 1. Gait Posture, 2001, 13(3), 247, doi:10.1016/j.gaitpost.2008.10.060

[16] GORTON G., HEBERT D., GOODE B., *Assessment of the kinematic variability between 12 Shriner's motion analysis laboratories*. Part 2. *Short term follow-up*, Gait Posture, 2002, 16(S1), 65–66.

[17] CHESTER V.L., TINGLEY M., BIDEN E.N., *Comparison of two normative paediatric gait databases*, Dyn. Med., 2007, 6, 8. doi:10.1186/1476-5918-6-8

[18] KADABA M., RAMAKRISHNAN H., WOOTTEN M., GAINEY J., GORTON G., COCHRAN G., *Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait*, Journal of Orthopaedic Research, 1989, 7(6), 849–860.

[19] DAVIS R.B., OUNPUU S., TYBURSKI D., GAGE J.R., *A gait analysis data collection and reduction technique*, Human Movement Science, 1991, 10, 575–587.

[20] TABAKIN D., VAUGHAN C.L., *A comparison of 3D gait models based on the Helen Hayes marker set*, Proceedings of the Sixth International Symposium on the 3D Analysis of Human Movement Cape Town, South Africa, 2000, 98–101.

[21] WHITTLE M.W., *Clinical gait analysis: A review*, 1996, 15(3), 369–387.

[22] KETTELKAMP D.B., JOHNSON R.J., SMIDT G.L., CHAO E.Y., WALKER M., *An electrogoniometric study of knee motion in normal gait*, J. Bone Joint Surg., 1970, 52-A, 775–790.

[23] WHITTLE M.W., *Gait analysis: An introduction* (4th Edition), Butterworth-Heinemann, Oxford, 2002.