Perceptual and Motor Skills, 2009, 109, 3, 851-869.

ANALYSIS OF KINEMATICS OF THE LOWER LIMB DURING STEP EXERCISE[1, 2]

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Summary.—The motion of lower extremity joints is one of the mechanisms by which mechanical load is attenuated. The main purposes of this study were to characterize the motion of the right lower limb in a group of 18 women experienced in step exercise, when performing selected step patterns, and to investigate the differences that exist between four stepping rate conditions (125, 130, 135, and 140 beats per minute) and between four step patterns (basic step, knee lift, run step, and knee hop). The parameters explored were the range-of-movement and angular velocity of hip, knee, and ankle joints at initial contact and peak values. The four movement patterns analyzed presented different kinematical profiles, but no profiles were influenced by stepping rate. Stepping rate and step pattern had more effect on range of motion of ankle and knee joints, and on the angular velocity of knee and hip joints. To prevent injury, proper instruction should be provided in relation to foot placement on the step bench and on the ground.

Step exercise has been promoted as a low-impact physical activity recommended for the improvement of cardiorespiratory fitness (Scharff-Olson, Williford, Blessing, & Brown, 1996). The description of step exercise characteristics is provided elsewhere (Santos-Rocha, Oliveira, & Veloso, 2006). The intensity of the workout can be controlled by adjusting the bench height (10 to 25 cm, usually 15 cm), adjusting the stepping rate (125 to 150 beats per minute), choosing the type of movements included in choreography (e.g., propulsive movements), and by adjusting the complexity of choreography (e.g., complex variations of basic steps and pro-

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[2]The authors wish to thank all participants of this study; Carlos Ferreira, Ph.D. (Faculty of Human Kinetics), for his contribution to this manuscript; Maria de Fátima Ramalho, M.Sc. (Sport Sciences School of Rio Maior), for her help in data collection; Pedro Aguiar, M.Sc. (National School of Public Health), and Isabel Carita, Ph.D. (Faculty of Human Kinetics), for their advice in statistical procedures.

gressions). This activity provides a certain amount of mechanical load, important for the improvement of bone health and other biological structures, because the number of loading cycles is related to the prevention of osteopenia and osteoporosis (Wilde, Sidman, & Corbin, 2001). One particular source of loading on the body is the ground reaction force (Hamill & Caldwell, 2001). Load repetition generally does not result in injury during normal activity, although it has been suggested that repeated impacts, such as the collision of the foot with the ground during locomotion, can result in microtrauma. However, the human body has a number of mechanisms by which load is attenuated. During ballistic locomotion and landing activities, the lower extremity joints must function synchronously to dissipate impact (Tillman, Hass, Chow, & Brunt, 2005). The body has structures such as fat pads on the plantar surface of the foot, articular cartilage in the joints and bone, and soft tissues surrounding the bone; there are also particular motions of the segments that attenuate shock. In the lower extremity, these include knee flexion, subtalar pronation, and ankle dorsiflexion (Hamill & Caldwell, 2001).

Kinematics provides a set of measurements that are often used to understand the motion characteristics of a movement and to identify differences between individuals, groups of individuals, or specified conditions. Despite more than 10 years of existence, the kinematics of step exercise have not yet been published. Understanding the kinematics of the lower limbs during this exercise might help instructors to give proper technique instructions to participants. Also, if the increase of stepping rate leads to an increase of exercise intensity, adjustments to lower limb kinematics may be needed.

Therefore, the main purposes of this study were to characterize selected kinematics parameters of the lower limb during step exercise, such as angular displacement (DZ), and angular velocity (VZ) of the ankle, knee, and hip joints, in a group of 18 skilled women, and to investigate the differences between four stepping rate conditions (125, 130, 135, and 140 bpm) and between four step patterns (basic step, knee lift, run step, and knee hop), performed with the right leading leg, in relation to the range of movement and angular velocity. These parameters were explored concerning ascending (forward) and descending (backward) phases of movements.

In relation to this second purpose, differences are expected in range of movement of the ankle, knee, and hip joints between the four stepping rate conditions and between the four step patterns.

Specifically, differences between the angular position of each joint at initial contact (DZi), and at peak (DZp) and angular velocity of the ankle, knee, and hip, at initial contact (VZi) and at peak (VZp) should be observed. The study should provide information about the kinematics of the lower limb during selected step patterns and how experienced subjects deal with the increase of movement cadence in terms of lower limb adjustments.

METHOD

Participants

Eighteen women experienced in step exercise (*M* age = 29.1 yr., *SD* = 6.8; *M* body mass = 58.9 kg, *SD* = 6.4; *M* height = 1.66 m, *SD* = 0.06; all were Caucasian) with no history of foot, ankle, or knee musculoskeletal or neuromuscular trauma or disease, who volunteered to participate in the study, were led through a sequence of stepping tasks. Previous to data collection, body height of the subjects was measured and body weight was measured using the Kistler force platform. These women were experienced fitness instructors who were certified and/or graduated in sport sciences and had at least 3 yr. of teaching experience in step exercise. After being informed about the aims and procedures of the investigation, all subjects were screened for health status (American College of Sports Medicine, 2000) and gave their consent to participate in the study before performing any exercise trials. The study was approved by the review committee of the faculty.

Procedure

Four step patterns were performed using right and left leading legs, resulting in a sequence of eight step patterns. This procedure was adopted to ensure mechanical balance between both lower limbs. The following sequence was performed in the laboratory using two force platforms (one for stepping up and the other for stepping down) at the cadences of 125, 130, 135, and 140 bpm: right basic step, right knee lift step, left basic step, left knee lift step, right run step, right knee hop step, left run step, and left knee hop step. None of the subjects felt discomfort during stepping over the two force platforms; also, it did not appear that the laboratory conditions had influenced their stepping style. Step performance did not change when stepping on a force plate compared to a bench. The protocol was tested by Santos-Rocha and Veloso (2007). The subjects were allowed to familiarize with each speed by performing a few steps before data collection. They were allowed as many practice trials as they wished prior to testing. Each participant was given approximately 60 to 90 seconds of rest between trials so as to reduce the potential effects of fatigue. For each condition of stepping rate, one successful sequence was collected.

These movements were performed in sequence, to better represent the real conditions of practice. No arm movements were added. These techniques were chosen because they are common in step exercise classes

(Santos-Rocha, *et al.*, 2006); they differ concerning the single or alternated leading leg; and they differ concerning the existence of propulsion during the movement or not. Each cycle is divided into ascending and descending phases and four steps: 1st step up (lead leg), 2nd step up (impulsion leg), 1st step down (lead leg), and 2nd step down (impulsion leg).

Regular music was used to maintain cadence. All experimental trials were conducted in a "crescent cadence" order, from 125 to 140 bpm. This procedure was adopted so the result would reflect typical conditions in a step exercise class. The cadence of 125 bpm is considered to be "slow," 130 bpm is a "regular" cadence, 135 bpm is "regular/fast," and 140 bpm is a "fast" cadence. Verbal instruction was provided during the tests. Participants wore similar Reebok® sport shoes during data collection, to reduce error due to the influence of the type of shoe on impact, braking, and propulsive forces (Hennig & Milani, 1995; Mitchell, Dyson, McMorris, Smith, & Hurrion, 1996). Fatigue was prevented by the short duration of the data collection session.

Ground reaction force curves were synchronized with kinematic data in order to better describe the movements. The movements were performed on the AMTI force platform (Advanced Mechanical Technology, Inc., Watertown, MA) of 0.90 m × 0.60 m × 0.17 m (length, width, height) for stepping up (ascending phase) and on the Kistler force platform (Kistler AG, Winterthur, Switzerland) of 0.60 m × 0.40 m (length, width) at the ground level for stepping down (descending phase). Ground reaction forces were measured at 1000 Hz and processed using AcqKnowledge 3.7.3 (Biopac Systems, Inc., Goleta, CA). The force data are explored elsewhere (Santos-Rocha, Veloso, & Machado, 2009).

Digital images were collected at the same time as the ground reaction forces. Spherical reflective markers were placed with double-sided adhesive tape on the skin and on the shoe, and on the left and right sides of the body (see Fig. 1). One digital video camcorder (JVC GR-DVL-9800) was placed at a distance of 3 m orthogonal to the plane of motion, capturing the right view of the body. A calibration frame (1.80 m × 1.80 m) was set around the center of the laboratory at ground level and was used just before or after each subject's data collection. Digital image of the whole body was captured at 50 Hz using the Analysis Performance Ariel System (APAS; Ariel Dynamics, Inc., San Diego, CA) CapDv module. Images were synchronized with force data using a light-emitting diode. Image data were trimmed using APAS Trimmer: the initial movement was defined using a vertical ground reaction force curve with the right basic step, in which the right foot touches the AMTI platform with a threshold of 10% of body weight. This sequence ends with a left knee hop step when the right foot descends and joins the left foot on the Kistler platform.

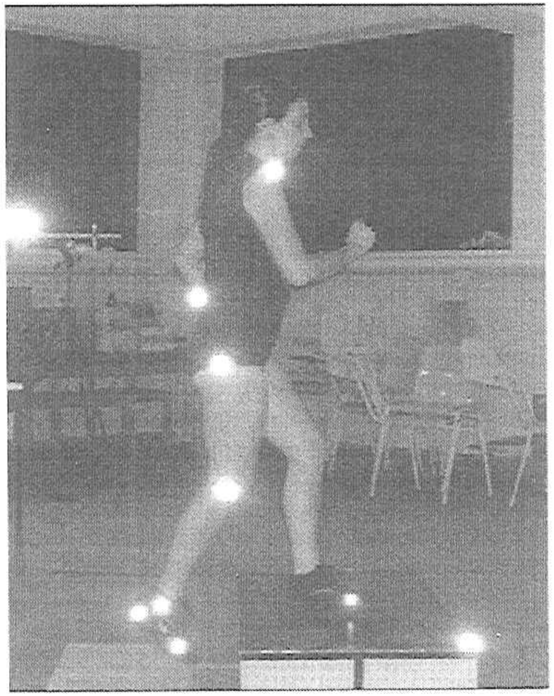

Fig. 1. Image of the spherical reflective markers placed on subjects

Data were digitized (APAS Digitize and Transform) and filtered with a low pass digital filter at 5 Hz (APAS Filter), to measure coordinates for the 5th metatarsal head, the calcaneus, the lateral malleolus, the lateral femoral epicondyle, the greater trochanter, and the shoulder, and to obtain kinematic parameters (APAS Display).

The linear and angular displacement data obtained at 50 Hz were interpolated using cubic splines with polynomial interpolants that have the characteristic of preserving the concavity of the interpolated data, as proposed by Robertson, Caldwell, Hamill, Kamen, and Whittlesey (2004) and Silva and Ambrósio (2005). Therefore, the force curves obtained at 1000 Hz were synchronized with kinematics data. Using MATLAB-7 (The MathWorks, Natick, MA), a resampling routine from 50 to 1000 Hz was built to transform the linear and angular displacement data. The angular velocity was calculated by derivation in MATLAB.

The curves of the angular displacement and angular velocity in ankle, knee, and hip joints were displayed in AcqKnowledge, together with vertical ground reaction force curves (normalized to body weight). In each condition of stepping rate, the kinematics and kinetics trajectories of all subjects were normalized in time, and the average curve was calculated (with standard deviation). Therefore, the average curves of each parameter were found for the 18 subjects in each condition, which were displayed graphically. Four of the eight movements performed in sequence were analyzed (basic step, knee lift, run step, and knee hop with right leading leg).

Biomechanical Parameters and Statistical Analysis

Considering ascending and descending phases of four step patterns performed at varying cadences, the curves of the following biomechanical parameters were calculated in relation to the total time of contact: DZ, the angular displacement in ankle, knee, and hip (in deg.); VZ, the angular velocity in ankle, knee, and hip (in deg./sec.); ground reaction force, the vertical component of the ground reaction force during ascending and descending phases (in N).

The joint angle at initial contact (DZ_i) and the peak value (DZ_p) of ascending and descending phases were collected in AcqKnowledge. The range of movement (difference between DZ_p and DZ_i) of each joint was calculated in Excel. Initial contact parameters were collected at the frame corresponding to 10% body weight in the vertical ground reaction force curve. Santos-Rocha, *et al.* (2009) have shown that greater loads occur during the contact on the step bench (in movements with propulsion) and during the contact on the ground (in movements without propulsion).

Considering the vertical ground reaction force during ascending phase (AscFz) of basic step and knee lift: the first peak corresponds to the first contact of foot on the step bench; the second peak corresponds to weight transfer between both feet, or to the knee lift, keeping the support on one foot; the third peak corresponds to the impulsion prior to backward descending. In the run step and knee hop, the first and second peaks correspond to the first and second leap or hop on the step bench. During the descending phase, the force profiles of the four movements are similar: the first peak corresponds to contact with the ground; the second peak refers to weight transfer on the ground; and the third peak corresponds to the propulsion prior to forward ascending of the next movement. Kinematic adjustments were monitored in AcqKnowledge with the following variables used as input for the statistical analysis: range of movement of ankle, knee, and hip joints between initial contact and peak (deg.); VZ_i, the ankle, knee, and hip joint angular velocities at initial contact (deg./sec.); and VZ_p, the ankle, knee, and hip joint peak angular velocities (deg./sec.).

All statistical procedures were conducted using SPSS software for Windows (Statistical Package for the Social Sciences, Chicago, IL). In addition to descriptive statistics, a one-way analysis of variance (ANOVA) for repeated measures was used to assess whether there were significant differences in kinematic parameters between the four conditions of stepping rate and the four step patterns, resulting in two within-subjects factors. Prior to calculating this ANOVA, Kolmogorov-Smirnov normality test and Mauchly's test of sphericity were conducted. In all cases, normality was assumed. In most cases, sphericity was assumed. In the cases in which sphericity was not assumed the Huynh-Feldt correction was used. The pairwise comparisons with the Bonferroni confidence interval adjustments were used to identify where differences could be found. In all cases, the level of statistical significance was set at $p \leq .05$ (Vincent, 2005).

Results

The following kinematic analysis refers to the right lower limb performing the right basic step, right knee lift, right run step, and right knee hop. Figs. 2 and 3 represent the overlapped average curves of angular displacement of joints and vertical ground reaction force (to better identify the movements) obtained for the 18 subjects in the four stepping rate conditions analyzed, for the ascending and descending phases of each step pattern. Tables 1 to 3 show the descriptive statistics for hip, knee, and ankle range of movement, VZ_i at initial contact and peak VZ, as well as the results of statistical analysis (ANOVA and Bonferroni pairwise comparisons).

The four patterns analyzed showed a motion forwards and upwards during the first half of the movement, corresponding to the ascending phase, and a motion backwards and downwards during the second half, corresponding to the descending phase of the movement. Subjects kept the same trajectory performing the movements at different cadences. These profiles varied between step patterns, especially during ascending phase, as expected, however each profile appear to be relatively stable and unrelated to stepping rate.

The lower extremity angles varied throughout the movement, particularly during the transition from the ascending phase to the descending phase of the movement. In the basic step, greater flexion of the knee and hip joints occurred during the first peak of force of the descending phase. At the same time, the ankle presented a dorsiflexion. In the knee lift condition, greater hip and knee flexion occurred before initial contact. Greater knee flexion occurred after the first peak of force in the ascending phase, together with dorsiflexion. In the run step, greater knee extension occurred after the first leap in the ascending phase, after which the knee and hip were in flexion until the peak flexion that occurred after the second leap. Then both joints extended. In the knee hop, greater knee flexion and ankle dorsiflexion occurred after the first peak of force during the hop in the ascending phase, followed by hip flexion (see Table 1).

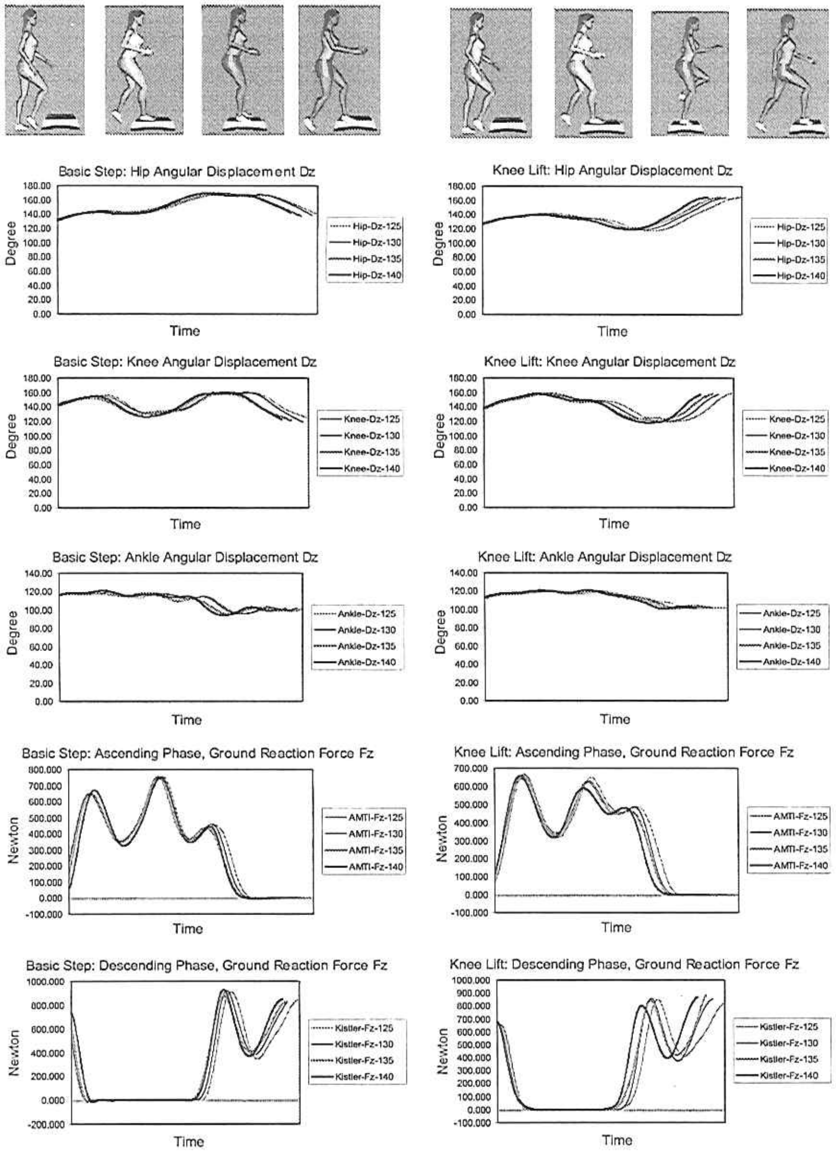

FIG. 2. Mean curves ($N = 18$): for the angular displacement (deg.) of the hip joint, knee joint, and ankle joint; for the vertical (Fz) component of the ground reaction force (N), in relation to time (sec.), during the ascending and descending phases of basic step and knee lift, performed at the cadences of 125, 130, 135, and 140 beats per minute.

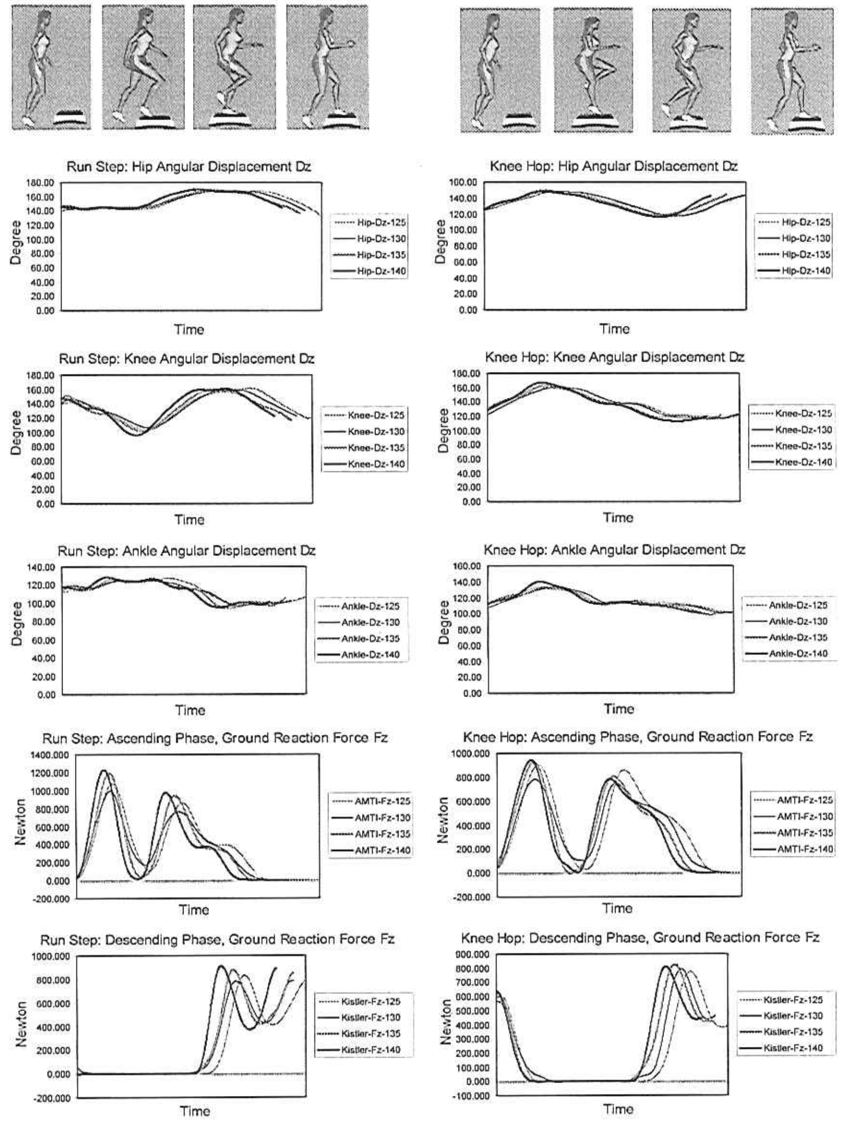

FIG. 3. Mean curves ($N = 18$): for the angular displacement (deg.) of the hip joint, knee joint, and ankle joint; for the vertical (Fz) component of the ground reaction force (N), in relation to time (sec.), during the ascending and descending phases of run step and knee hop, performed at the cadences of 125, 130, 135, and 140 beats per minute.

TABLE 1

JOINT DISPLACEMENT VARIABLES: MEANS AND STANDARD DEVIATIONS OF HIP, KNEE, AND ANKLE RANGE OF MOVEMENT BETWEEN INITIAL CONTACT AND PEAK (DEG.) OF RIGHT LOWER LIMB, DURING ASCENDING PHASE (CONTACT WITH BENCH) AND DESCENDING PHASE (CONTACT WITH FLOOR), FOR FOUR STEP PATTERNS PERFORMED AT FOUR STEPPING RATES (BPM). SUMMARY OF ANALYSES OF VARIANCE FOR CONDITIONS OF STEPPING RATE AND STEP PATTERN

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Hip Range of Movement, deg.																
M	19.72	19.39	18.67	17.89	23.11	20.39	19.06	18.78	13.94	11.28	11.17	9.06	29.00	27.89	26.28	23.83
SD	8.76	8.51	9.89	9.00	8.33	9.08	9.27	10.02	5.02	7.34	7.39	6.77	8.54	11.03	12.69	12.03
Stepping Rate	No differences															
Step Pattern	$F_{2.115,37.662}$=123.263 ($p<.001$); All *post hoc* comparisons significant at $p=.013$															
Descending Phase–Hip Range Of Movement, deg.																
M	3.44	4.22	4.11	3.50	24.46	25.62	24.85	25.11	3.00	3.72	3.56	3.06	27.25	24.45	26.38	26.89
SD	4.13	4.62	3.48	3.35	26.82	29.11	26.85	27.22	3.97	4.85	4.34	4.44	27.05	27.97	26.58	26.79
Stepping Rate	No differences															
Step Pattern	No differences															
Ascending Phase–Knee Range of Movement, deg.																
M	23.72	22.94	21.11	21.11	34.06	32.67	30.83	29.72	21.06	16.44	14.28	13.06	49.72	45.74	42.17	42.82
SD	11.09	11.35	12.34	11.07	7.88	10.24	12.85	11.74	8.94	8.12	8.94	7.63	8.27	13.66	17.23	15.86
Stepping Rate	$F_{1.942,33.008}$= 6.267 ($p=.005$); *Post hoc* comparisons: 125 versus 140 bpm ($p=.042$); 130 versus140 bpm ($p=.021$)															
Step Pattern	$F_{2.043,34.728}$= 64.101 ($p<.001$); All *post hoc* comparisons significant ($p<.001$), except for run step															
Descending Phase–Knee Range of Movement, deg.																
M	9.50	9.78	10.44	10.61	6.00	12.33	13.00	12.61	10.11	10.06	9.22	10.00	8.56	12.60	12.56	17.06
SD	5.42	4.48	5.87	5.81	10.32	17.11	18.19	17.85	7.69	7.15	5.91	6.41	13.43	15.43	13.69	17.99
Stepping Rate	$F_{3,51}$=5.926 ($p=.002$); *Post hoc* comparisons: 125 versus 140 bpm ($p=.023$)															
Step Pattern	No differences															

(continued on next page)

TABLE 1 (CONT'D)

JOINT DISPLACEMENT VARIABLES: MEANS AND STANDARD DEVIATIONS OF HIP, KNEE, AND ANKLE RANGE OF MOVEMENT BETWEEN INITIAL CONTACT AND PEAK (DEG.) OF RIGHT LOWER LIMB, DURING ASCENDING PHASE (CONTACT WITH BENCH) AND DESCENDING PHASE (CONTACT WITH FLOOR), FOR FOUR STEP PATTERNS PERFORMED AT FOUR STEPPING RATES (BPM). SUMMARY OF ANALYSES OF VARIANCE FOR CONDITIONS OF STEPPING RATE AND STEP PATTERNN

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Ankle Range of Movement, deg.																
M	6.28	6.56	6.89	7.67	12.56	12.50	13.57	13.28	24.52	18.72	17.94	16.33	41.52	38.06	34.08	33.72
SD	3.46	4.51	5.89	6.31	5.52	4.44	6.63	6.13	10.78	8.84	8.81	6.12	7.13	7.63	12.27	8.61
Stepping Rate	$F_{2.102,35.737}$=7.416 ($p=.002$); *Post hoc* comparisons: 125 versus 140 bpm ($p=.003$)															
Step Pattern	$F_{3,51}$=47.465 ($p<.001$); All *post hoc* comparisons significant ($p<.001$), except for knee lift															
Descending Phase–Ankle Range of Movement, deg.																
M	3.38	2.66	2.99	2.80	0.56	1.17	1.44	1.22	4.02	4.04	2.82	4.00	2.67	2.94	3.28	3.59
SD	5.35	3.52	4.63	5.04	1.15	1.38	1.95	2.13	5.69	5.87	4.32	6.71	3.05	3.32	3.18	3.52
Stepping Rate	No differences															
Step Pattern	$F_{1.072,18.221}$=14.890 ($p=.001$); *Post hoc* comparisons: basic step versus knee lift ($p=.011$); basic step versus knee hop ($p=.005$); knee lift versus run step ($p=.009$); run step versus knee hop ($p=.005$)															

During the ascending phase, the ankle range of movement values increased as stepping rate increased. No statistical differences were observed between conditions of stepping rate. Significant differences were found between all step patterns. During the descending phase, the ankle range of movement increased as the stepping rate increased. No statistical differences were observed between stepping rates, and no differences were observed between step patterns.

During the ascending phase, the knee range of movement values in all conditions decreased as the stepping rate increased. Significant differences were found between stepping rates and between step patterns. During the descending phase, the knee range of movement in all conditions increased as the stepping rate increased. Significant differences in knee range of movement were found between stepping rates, but no differences were observed between step patterns.

During the ascending phase, the hip range of movement values decreased in all conditions as the stepping rate increased. Significant differences were found between stepping rates and between step patterns. During the descending phase, no significant differences were observed between stepping rates, but significant differences were found between step patterns.

Coefficients of variation (*CV*) showed that the positional variables at the ankle, knee, and hip were more variable at faster stepping rates, indicating that kinematic changes occurred as a function of increased stepping velocity. During initial contact both in ascending and descending phases of the four movements, joint angles increased as the stepping rate increased, particularly in the ankle and knee joints, also indicating kinematics adaptation as a function of increased stepping velocity. However, statistical differences were found only in the ascending phase. The DZ_p and the range of movement from DZ_i to DZ_p during reception appear to decrease as the stepping rate increased, due to a shorter interval time to perform the movement. As expected, different step patterns were related to adaptations in joint angles during the ascending phase, but not during the descending phase, perhaps because technique for this phase is similar for the four movements analyzed. More kinematic adaptations were observed in the knee joint, which presented a greater range of movement.

During the ascending phase, the ankle VZ_i (Table 2) showed no statistically significant differences between stepping rates and between step patterns. The ankle VZ_p (Table 3) showed no statistically significant differences between stepping rates, but significant differences were found between all step patterns. During the descending phase, the ankle VZ_i showed no statistically significant differences between stepping rate or between step patterns. The ankle VZ_p increased as the stepping rate increased; significant differences were found between stepping rates and between step patterns. During the ascending phase, the knee VZ_i increased as the stepping rate increased; significant differences were found between stepping rates and between step patterns. Concerning the knee VZ_p no statistical differences were observed between stepping rates, but significant differences were found between all step patterns. During the descending phase, the knee VZ_i showed no statistical differences between stepping rates, but significant differences were found between step patterns. The knee VZ_p increased as the stepping rate increased. Significant differences were found between conditions of stepping rate but not between step patterns.

During the ascending phase, the hip VZ_i increased as the stepping rate increased, and significant differences were found between stepping rates. The hip VZ_p showed no differences between stepping rates, but significant differences were found between step patterns. During the descending phase, the hip VZ_i increased as the stepping rate increased, with significant differences between stepping rates and between step patterns. The hip VZ_p increased as the stepping rate increased; significant differences were found between stepping rates and between step patterns.

The VZ of the three joints presented several variations throughout the movements, especially in the ankle joint. Peaks of greater magnitude were observed in the knee joint.

Discussion

The present investigation provides data for kinematic parameters of step patterns that may be used as a basis of comparison with older and novice step participants in future biomechanical research. No results were found in the literature to be compared with these results.

The profiles of joint DZ did not change with stepping rate. While stepping at different rates, the kinematic parameters were very regular and repetitive between subjects, despite different intervals associated with the stepping rates (number of steps per minute). The main adaptations occurred in the knee joint angles and velocity.

During initial contact both in ascending and descending phases of the four movements, the joint angles increased as the stepping rate increased, particularly in the ankle and knee joints, also indicating kinematic adaptation as a function of increased stepping velocity. However, statistically significant differences were found only in the ascending phase. The DZ_p and the range of movement from DZ_i to DZ_p appear to decrease as the stepping rate increased, due to a shorter interval time for performing the movement. As expected, different step patterns affected the adaptations in joint angles during the ascending phase, but not during the descend-

TABLE 2

Joint Velocity Variables: Means and Standard Deviations For Hip, Knee, and Ankle Angular Velocity at Initial Contact (deg./sec.) of Right Lower Limb, During Ascending Phase and Descending Phase, For Four Step Patterns Performed at Four Stepping Rates (bpm). Summary of Analyses of Variance For Conditions of Stepping Rate and Step Pattern

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Hip Angular Velocity at Initial Contact, deg./sec.																
M	83.20	90.51	95.35	100.07	61.49	63.22	69.91	75.56	105.99	97.28	85.12	97.63	104.10	137.41	130.38	150.72
SD	38.93	41.57	43.47	38.65	27.69	30.26	38.26	35.58	71.42	54.06	74.86	69.31	53.85	52.23	60.93	51.75
Stepping Rate	$F_{2.413,41.016}=3.942$ ($p=.021$); 125 versus 140 bpm ($p=.007$)															
Step Pattern	$F_{2.613,44.426}=53.059$ ($p<.001$); *Post hoc* comparisons: basic step versus knee hop ($p=.011$); knee lift versus knee hop ($p<.001$)															
Descending Phase–Hip Angular Velocity at Initial Contact, deg./sec.																
M	15.00	32.01	50.58	52.49	−63.26	−41.71	−24.19	−32.48	4.32	26.49	41.54	24.81	−47.10	−30.60	−25.38	−17.10
SD	52.57	52.09	56.03	45.22	53.86	80.08	117.77	101.84	35.80	40.09	35.58	38.78	64.69	73.38	110.79	97.63
Stepping Rate	$F_{2.005,34.080}=6.320$ ($p=.005$); *Post hoc* comparisons: 125 versus 135 bpm ($p=.044$); 125 versus 140 bpm ($p=.021$)															
Step Pattern	$F_{1.328,22.575}=8.333$ ($p=.005$); *Post hoc* comparisons: basic step versus knee lift ($p=.021$)															
Ascending Phase–Knee Angular Velocity at Initial Contact, deg./sec.																
M	84.15	87.74	81.20	93.00	56.51	100.88	96.01	106.02	111.16	124.95	92.81	104.55	122.29	179.28	156.49	194.54
SD	67.62	78.94	77.64	73.46	79.66	78.00	87.15	77.16	189.76	154.97	157.82	194.45	137.19	154.57	163.96	162.27
Stepping Rate	$F_{3,51}=5.240$ ($p=.003$); *Post hoc* comparisons: 125 versus 130 bpm ($p=.013$); 125 versus 140 bpm ($p=.009$)															
Step Pattern	$F_{1.684,23.630}=6.629$ ($p=.006$); *Post hoc* comparisons: basic step versus knee hop ($p=.015$); knee lift versus knee hop ($p=.015$); run step versus knee hop ($p=.009$)															
Descending Phase–Knee Angular Velocity at Initial Contact, deg./sec.																
M	75.25	109.79	123.83	135.28	−116.49	−145.77	−121.42	−149.06	49.30	98.89	115.77	101.89	−120.29	−122.58	−108.99	−120.48
SD	76.89	82.45	93.82	84.53	104.85	107.77	116.31	125.27	84.33	88.13	95.28	71.78	121.98	125.74	145.68	126.18
Stepping Rate	No differences															
Step Pattern	$F_{1.189,20.205}=75.606$ ($p<.001$); *Post hoc* comparisons: basic step versus knee lift ($p<.001$); basic step versus knee hop ($p<.001$); knee lift versus run step ($p=.001$); run step versus knee hop ($p<.001$)															

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TABLE 2 (cont'd)

Joint Velocity Variables: Means and Standard Deviations For Hip, Knee, and Ankle Angular Velocity at Initial Contact (deg./sec.) of Right Lower Limb, During Ascending Phase and Descending Phase, For Four Step Patterns Performed at Four Stepping Rates (bpm). Summary of Analyses of Variance For Conditions of Stepping Rate and Step Pattern

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Ankle Angular Velocity at Initial Contact, deg./sec.																
M	39.90	45.77	52.99	55.66	40.34	60.88	66.77	78.26	41.27	74.13	62.83	59.90	85.59	127.87	118.98	127.71
SD	50.86	47.07	49.27	47.02	30.29	15.93	25.11	21.39	187.44	205.76	192.14	247.69	107.51	154.22	151.72	191.20
Stepping Rate	No differences															
Step Pattern	No differences															
Descending Phase–Ankle Angular Velocity at Initial Contact, deg./sec.																
M	−60.27	−15.52	−24.36	−44.11	−23.61	−11.21	−4.76	−9.64	−80.03	−31.26	−31.74	−31.86	−8.65	−7.62	10.01	10.54
SD	120.07	82.99	85.71	93.41	61.99	50.60	52.34	44.40	116.50	78.27	97.16	94.31	67.38	71.74	72.30	50.28
Stepping Rate	No differences															
Step Pattern	No differences															

TABLE 3

Joint Velocity Variables: Means and Standard Deviations of Hip, Knee, and Ankle Peak Angular Velocity (deg./sec.) and of Right Lower Limb, During Ascending and Descending Phase, For Four Step Patterns Performed at Four Stepping Rates. Summary of Analyses of Variance For Conditions of Stepping Rate and Step Pattern

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Hip Peak Angular Velocity During Reception, deg./sec.																
M	108.07	110.61	118.29	115.49	108.82	105.81	108.64	111.12	164.12	161.87	165.05	161.33	203.22	201.83	193.90	206.89
SD	21.85	29.66	33.24	33.46	28.39	19.86	26.46	31.87	32.72	46.69	52.06	46.24	32.05	37.18	52.13	49.88
Stepping Rate	No differences															
Step Pattern	$F_{2.613,44.426}=53.059$ ($p<.001$); *Post hoc* comparisons all $ps=.003$, except basic step versus knee lift															
Descending Phase–Hip Peak Angular Velocity During Reception, deg./sec.																
M	64.60	70.86	83.41	77.07	230.78	247.72	252.17	266.50	60.98	61.88	68.21	61.58	219.78	220.78	236.50	248.94
SD	35.74	32.98	33.52	30.65	60.56	52.71	47.88	42.98	30.07	32.56	27.99	28.62	64.04	53.07	64.99	53.02
Stepping Rate	$F_{2.565,43.606}=8.645$ ($p<.001$); *Post hoc* comparisons: 125 versus 135 bpm ($p=.004$); 125 versus 140 bpm ($p<.001$); 130 versus 140 bpm ($p=.037$)															
Step Pattern	$F_{3,51}=184.435$ ($p<.001$); *Post hoc* comparisons: basic step versus knee lift ($p<.001$); basic step versus knee hop ($p<.001$); knee lift versus run step ($p<.001$); run step versus knee hop ($p<.001$)															
Ascending Phase–Knee Peak Angular Velocity During Reception, deg./sec.																
M	148.89	155.27	151.37	155.51	187.72	193.00	191.28	198.67	332.33	321.89	303.02	328.72	385.72	375.94	363.83	377.78
SD	36.88	46.49	46.82	44.07	43.59	44.57	54.00	50.33	64.97	65.56	87.82	50.91	57.05	42.85	71.15	58.48
Stepping Rate	No differences															
Step Pattern	$F_{2.581,43.873}=173.516$ ($p<.001$); *Post hoc* comparisons: all $ps=.007$															
Descending Phase–Knee Peak Angular Velocity During Reception, deg./sec.																
M	121.06	142.54	156.39	161.56	163.95	164.29	159.65	181.49	121.56	145.34	150.29	133.06	152.52	141.13	181.36	185.76
SD	59.18	69.48	76.20	76.99	125.54	160.93	141.11	140.29	57.09	75.58	76.22	69.59	141.37	148.27	152.16	165.98
Stepping Rate	$F_{3,51}=5.603$ ($p=.002$); *Post hoc* comparisons: 125 versus 135 bpm ($p=.008$); 125 versus 140 bpm ($p=.005$)															
Step Pattern	No differences															

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TABLE 3 (cont'd)

Joint Velocity Variables: Means and Standard Deviations of Hip, Knee, and Ankle Peak Angular Velocity (deg./sec.) and of Right Lower Limb, During Ascending and Descending Phase, For Four Step Patterns Performed at Four Stepping Rates. Summary of Analyses of Variance For Conditions of Stepping Rate and Step Pattern

	Basic Step				Knee Lift				Run Step				Knee Hop			
	125	130	135	140	125	130	135	140	125	130	135	140	125	130	135	140
Ascending Phase–Ankle Peak Angular Velocity During Reception, deg./sec.																
M	70.67	74.01	75.97	79.06	93.40	88.73	100.24	101.30	346.44	331.06	318.11	335.00	393.61	380.06	360.26	374.33
SD	32.75	45.94	42.52	46.05	36.66	22.35	43.06	35.20	59.23	43.23	54.52	40.87	50.84	47.12	77.53	43.57
Stepping Rate	No differences															
Step Pattern	$F_{3,51}=482.459$ ($p<.001$); *Post hoc* comparisons: all $ps=.014$															
Descending Phase–Ankle Peak Angular Velocity During Reception, deg./sec.																
M	79.43	86.02	107.34	107.11	22.50	33.97	39.65	35.99	87.99	93.02	94.76	111.56	39.08	53.44	72.73	79.22
SD	37.32	53.07	58.72	67.00	28.57	33.37	41.35	32.88	42.57	55.72	58.09	62.42	35.14	33.27	69.30	61.86
Stepping Rate	$F_{2.033,34.555}=11.933$ ($p<.001$); *Post hoc* comparisons: 125 versus 135 bpm ($p=.021$); 125 versus 140 bpm ($p=.013$)															
Step Pattern	$F_{3,51}=7.816$ ($p<0.001$); basic-knee lift ($p=0.003$); knee lift-run ($p=0.001$); knee lift-hop ($p=0.029$); Hypothesis confirmed; Greater values in basic step															

ing phase; the latter phase is similar for the four movements analyzed, in terms of technique.

The VZ of the three joints was a parameter that presented several variations throughout the movements, especially at the ankle joint. However, greater maximal values were observed in the knee joint.

Previous studies have shown that biomechanical intensity is related to bench height (10, 15, or 20 cm) and to stepping rate (122, 130, and 138 bpm; Hecko & Finch, 1996; Maybury & Waterfield, 1997; Santos-Rocha, Veloso, Santos, Franco, & Pezarat-Correia, 2002). In experienced participants, as stepping rate increases, the time interval to complete the step actions is decreased and lower limb muscle activation increases (Santos-Rocha, Pezarat-Correia, Franco, & Veloso, 2004). The results allow the conclusion that the kinematics of the lower limbs are affected by the step pattern and stepping rate.

Results indicated that increasing step frequency leads to an increase in the mechanical load, which appears to be supported by adaptations of the movement technique related to the increasing ground reaction force. These adaptations of kinematics and muscle activation are related to the way that the body manages force magnitudes and to the pattern of force-absorbing adjustments to ground reaction force and joint and muscle forces. However, if technique adaptations occur, especially in the knee joint, together with greater ground reaction force and decreased time for contact and force transfer, the stepping rate, being one of the most important determinants of exercise intensity, particularly above 135 bpm, should be chosen carefully in step classes, always considering the participants' experience in this activity.

The present results are based on a sample of 18 female step exercise instructors, who were physically active and had long experience in this activity. The kinematic characteristics might be different if participants with less experience in step were studied. Further research is required to understand how kinematic parameters can be modified with specific training.

REFERENCES

American College of Sports Medicine. (2000) *Guidelines for exercise testing and prescription.* (6th ed.) Baltimore, MD: Williams & Wilkins.

Hamill, J., & Caldwell, G. E. (2001) Mechanical load on the body. In M. Hauber (Ed.), *American College of Sports Medicine's resource manual for guidelines for exercise testing and prescription.* (4th ed.) Baltimore, MD: Williams & Wilkins. Pp. 107-112.

Hecko, K., & Finch, A. (1996) Effects of prolonged bench stepping on impact forces. In J. Abrantes (Ed.), *Proceedings of the XIV International Symposium on Biomechanics in Sports.* Lisbon, Portugal. Pp. 464-466.

Hennig, E. M., & Milani, T. L. (1995) In-shoe pressure distribution for running in various types of footwear. *Journal of Applied Biomechanics,* 11, 299-310.

Maybury, M. C., & Waterfield, J. (1997) An investigation into the relationship between step height and ground reaction forces in step exercise: a pilot study. *British Journal of Sports Medicine,* 31, 109-113.

Mitchell, A., Dyson, R., McMorris, T., Smith, N., & Hurrion, P. (1996) Relationship of shoe impact, braking and propulsive forces. In J. Abrantes (Ed.), *Proceedings of the XIV International Symposium on Biomechanics in Sports.* Lisbon, Portugal. Pp. 453-455.

Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2004) *Research methods in biomechanics.* Champaign, IL: Human Kinetics.

Santos-Rocha, R., Oliveira, C., & Veloso, A. (2006) Osteogenic index of step exercise depending on choreographic movements, session duration and stepping-rate. *British Journal of Sports Medicine,* 40, 860-866.

Santos-Rocha, R., Pezarat-Correia, P., Franco, S., & Veloso, A. (2004) Análise da participação muscular no passo básico de step: efeito da velocidade da música e da altura da plataforma. *Revista Brasileira de Biomecânica – Brazilian Journal of Biomechanics,* 5, 5-12. [In Portuguese, English abstract]

Santos-Rocha, R., & Veloso, A. (2007) Comparative study of plantar pressure during step exercise in different floor conditions. *Journal of Applied Biomechanics,* 23, 158-164.

Santos-Rocha, R., Veloso, A., & Machado, M. L. (2009) Analysis of ground reaction forces in step-exercise depending on step-pattern and stepping-rate. *Journal of Strength and Conditioning Research,* 23, 209-224.

Santos-Rocha, R., Veloso, A., Santos, H., Franco, S., & Pezarat-Correia, P. (2002) Ground reaction forces of step exercise depending on step frequency and bench height. In K. E. Gianikellis (Ed.), *Scientific Proceedings of the XX International Symposium on Biomechanics in Sports.* Cáceres, Spain. Pp. 156-158.

Scharff-Olson, M., Williford, H. N., Blessing, D. L., & Brown, J. A. (1996) The physiological effects of bench/step exercise. *Sports Medicine,* 21, 164-175.

Silva, M. T., & Ambrósio, J. C. (2005) Consequences of using kinematic interpolated data for the solution of the redundant problem in biomechanics. In H. Rodrigues, M. Cerrolaza, M. Doblaré, J. C. Ambrósio, & M. Viceconti (Eds.), *Proceedings of the ICCB 2005–II International Conference on Computational Bioengineering.* Vol. 2. Lisbon, Portugal: IST Press. Pp. 965-976.

Tillman, M. D., Hass, C. J., Chow, J. W., & Brunt, D. (2005) Lower extremity coupling parameters during locomotion and landings. *Journal of Applied Biomechanics,* 21, 359-379.

Vincent, W. J. (2005) *Statistics in kinesiology.* (3rd ed.) Champaign, IL: Human Kinetics. Pp. 171-185.

Wilde, B. E., Sidman, C. L., & Corbin, C. B. (2001) A 10,000-step count as a physical target for sedentary women. *Research Quarterly in Exercise and Sport,* 72, 411-414.

Accepted October 15, 2009.