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Kinematic analysis of obstacle clearance during locomotion

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Abstract

This study investigated the effect of obstacles of different heights on the locomotion of 15 healthy subjects. The following parameters were studied: (1) the distance of the toe and heel markers from the obstacle during toe-off and heel contact, respectively, (2) the minimum clearance distance of the toe and heel markers, and (3) the angular displacements and velocities of the hip, knee, and ankle. Results show significant differences in joint angular kinematics and clearance distances as obstacle height increased. The kinematic and distance differences exhibited both strong linear and non-linear trends. Toe-off distance and heel contact distance did not change significantly with changes in obstacle height. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Rarely is the path of locomotion perfectly level and clear. More commonly, during locomotion a person is confronted with a course consisting of undulations or obstacles. Obstacles of various heights, widths, depths and compositions require the actor to modify the movement pattern to either step over, step on, or circumnavigate the obstacle. Of the three available options, stepping over an obstacle places the greatest demands on the locomotor system and poses the greatest risks. The demands are created by the altered swing phase which may result in the emergence of a longer single limb support phase. The risk of stumbling or falling arises from either (1) the potential interference of the obstacle with the toe or heel of the swing limb or (2) the unstable and protracted stance phase in which the center of mass is outside of the narrow base of support. The result is the need for precision and accuracy during a period of great demand and instability. Remarkably, this demanding adjustment is typically made with little effort and great success. However, when the person fails to successfully negotiate the obstacle, the results can be disastrous.

Related research has focused on gait over level ground and the ascent and descent of stairs. Yet, obstacles to locomotion are frequently encountered in everyday activities. Tripping, stumbling, and falling are good examples of faulty execution by the locomotor system. Each year people of all ages, many of them elderly, sustain serious injuries from falls as a result of tripping over obstacles. In England more than 10 000 claims were brought in 1 year for injuries resulting from tripping over paving stones [1]. It is well documented that the incidence of falls is substantially greater in the older population, thus it is not surprising that the most theory and research in this area addresses this age group [2–5]. As the elderly population grows this problem will certainly demand more attention in the hopes of preventing falls and their costly and debilitating sequelae.

Going over an obstacle in one's path can involve varying degrees of difficulty and risk; extremes range from a crack in the floor to the pole vault in track and field. Midpoints along this spectrum of difficulty might include the daily acts of going over a curb, stepping over the wall of a bathtub, or the athletic challenges of clearing the high jump bar or consecutive intermediate hurdles [6–9].

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Recently, stepping over an obstacle has received more attention [6,10–19]. Results of descriptive kinematic studies focusing on the lead swing lower extremity show that rather than widespread alteration of the task as obstacle height increased, only speed was significantly decreased while crossing the obstacle. No significant obstacle height effects on toe or heel distance, step length, or step width have been reported. Also, foot clearance of the lead leg has been shown in two instances to increase notably in relation to increases in obstacle height [10,13]. However, Patla and Rietdyk [12] found toe clearance to remain invariant across several obstacle heights. None of the three studies reported a decrease in the margin of toe, heel, or foot clearance as obstacle height increased [10,12,13].

In studying strategies utilized for going over obstacles, Patla et al. [11] found that subjects appeared to utilize information regarding the various locations and heights of the obstacles to employ the most appropriate strategy for achieving success at the task. In a computer simulation, Taga [15] demonstrated the importance of environmental information to the emerging dynamics of obstructed gait. Significant constraints seemed to be placed on movement strategies by safety/stability and efficiency/economy considerations [11,14].

Winter [20] investigated gait over level ground and reported a toe clearance of 1.29 cm at mid-swing with a variability of only 0.45 cm for 11 subjects (a value for heel clearance was not presented). Winter [20] also reported a sensitivity analysis which quantified the angular changes at the hip, knee, and ankle which could account for the 0.45-cm variability in toe clearance. Toe clearance is sensitive to angular changes as small as 1.35–2.16° at the ankle, hip, or knee of the swing limb. The minimal and precise modification of movement is suggestive of parsimony, safety, and efficiency in the kinematics of clearing an obstacle. Certainly, the precision of both the leading and trailing lower extremities, as well as the efficiency of the clearance of the hurdle are foci of instruction in the techniques of hurdling [7–9,21].

To date empirical studies of the task of stepping over obstacles have yielded conflicting results with regard to clearance distances. The purpose of this study was to investigate: (1) the kinematics of the swing phase limb, (2) the minimum clearance distance during swing phase, and (3) the distance of distal endpoints from the obstacle during toe-off and heel contact during ambulation.

2. Methods

One group of 15 female subjects participated voluntarily in this study. In accordance with approval by the Human Subjects Review Committee at the University of Connecticut, all subjects read and signed an informed consent form prior to participation. All subjects were deemed to be free of lower extremity neuromusculoskeletal dysfunction and reported normal corrected vision. The subjects were required to be between the heights of 145 cm (2.5 percentile) and 173 cm (97.5 percentile) [22] (Table 1).

The heights of obstacles, constructed from wood, were chosen on the basis of their relevance to daily activities: (1) 31 mm (height of standard doorstop), (2) 76 mm (standard intermediate obstacle height), (3) 126 mm (height of standard curb or parking stone), and (4) 0 mm (a piece of tape on the floor). All obstacles were 300 mm in width and 25 mm in depth. Reflective tape was attached to the four corners of the side of the obstacle nearest to the video camera. One of the obstacles or a piece of tape was placed in the path of locomotion for each trial.

The data were collected by two-dimensional videography using the Peak Performance Technologies Motion Measurement System (Englewood, CO) with a standard sampling rate of 60 Hz and a shutter rate of 1/1000 s. Spherical reflective markers, 1 1/2 inch and 3/4 inch in diameter, were mounted via double-sided adhesives to the skin overlying anatomical landmarks on the lower extremity. Two reflective markers were attached to the right side of each of four segments: (1) foot—head of the fifth metatarsal and the lateral aspect of the calcaneus, (2) shank—lateral malleolus and fibular head, (3) thigh—lateral femoral condyle and greater trochanter, and (4) pelvis–two markers placed along a path from the anterior superior iliac spine to the posterior superior iliac spine (Fig. 1).

The subjects were videotaped performing three trials of each of the four conditions. The sequence of the trials was randomized. The data were captured from just prior to toe off to just after heel contact of the right limb. The subjects ambulated at a comfortable self-selected speed, beginning 4 m from the obstacle.

The displacement and velocity values were calculated after the raw data were filtered with a low pass, fourth order Butterworth digital filter at a cut-off frequency of 6 Hz. Distances were calculated from the conditioned coordinate data. Toe clearance was defined as the minimum clearance between the upper, proximal corner of the obstacle and the marker on the head of the fifth metatarsal during the swing phase. Heel clearance was defined as the minimum clearance between the distal, upper corner of the obstacle and the marker on heel

Table 1
Description of sample

	Age (years)	Height (cm)	Weight (kg)
Mean	26.3	160.4	57.2
Range	19–34	150.0–170.0	44.5–68.0

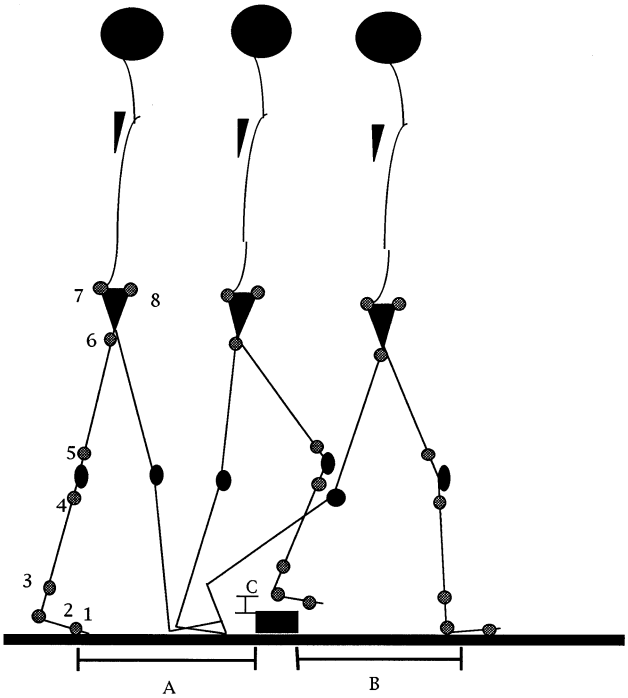

Fig. 1. Reflective marker set-up and distance illustration: (1) fifth metatarsal, (2) calcaneus, (3) lateral malleolus, (4) fibular head, (5) lateral femoral condyle, (6) greater trochanter, (7) posterior superior iliac spine, and (8) anterior superior iliac spine. Distances from obstacle: (A) toe from obstacle at toe off, (B) heel from obstacle at heel contact, and (C) clearance of heel and toe over obstacle.

during swing phase. Toe off distance was defined as the distance of the fifth metatarsal marker from the lower, proximal corner of the obstacle at toe off. Heel contact distance was defined as the distance of the heel marker from the lower, distal corner of the obstacle at heel contact. It should be noted that reported distances are of the markers from the obstacle and thus are not true amounts of limb clearance.

Descriptive statistics were calculated for all anthropometric and kinematic parameters for the entire sample and for the different height obstacles. A 4×3 (obstacle height $\times$ trials) repeated measures analysis of variance (RMANOVA) was conducted on the following dependent variables: angular displacements, angular velocities, toe off distance, toe clearance distance, heel clearance distance, and heel contact distance. The significance level was set at 0.05. Pairwise post hoc analysis of the RMANOVA results was performed to determine which means were significantly different from each other. A total of six pairs of means were compared, therefore to avoid type I errors, the level of significance was adjusted to 0.008, using Bonferroni's correction. Additionally, trend analysis was utilized to investigate the functional relationship among the heights of the obstacle and distance, angular displacement, and angular velocity.

3. Results

For the distance, angular displacement, and angular velocity data no statistically significant trial effects or interactions were found as a result of the RMANOVA. However, this was not the case with the height effect. Thus, the significant findings regarding the differences which follow are attributable to the effect of the height of the obstacle.

3.1. Toe off, clearance, and heel contact distances

RMANOVA of the distance data revealed significant height effects for toe clearance ($F = 90.456$, $P = 0.000$), heel clearance ($F = 51.562$, $P = 0.000$), and heel contact ($F = 3.426$, $P = 0.026$), but not for toe off ($F = 1.533$, $P = 0.220$). Upon pairwise post hoc analysis of the RMANOVA results for the toe and heel clearance distances, significant differences were shown to exist among all six pairs ($P = 0.000$), except for between the 76- and 126-mm heights ($P = 0.045$ and $P = 0.619$, respectively). Similar analysis of heel contact distances did not reveal a significant difference among any of the pairs. The largest F-values for the latter distance, although not significant at the 0.008 level, were found between the 0- and 76-mm heights, and the 0- and 126-mm heights ($F = 7.528$, $P = 0.016$ and $F = 7.342$, $P = 0.017$, respectively). Trend analysis of toe and heel clearance distances revealed strong linear and cubic trends, with a lesser quadratic trend whereas analysis of heel contact distances revealed a trend of a linear nature.

In the case of toe clearance the absence of a significant height effect for the difference of the means for the 76- and 126-mm heights along with the cubic polynomial trend point to the likelihood that a plateau of toe clearance distance occurs at the greater heights. As with toe clearance distance, heel clearance distance exhibited an overall linear tendency to increase with corresponding increases in the height of the obstacle. It should be noted that with both toe and heel clearance distance (1) the height effect became non-significant for the difference between the heights of the 76- and 126-mm heights, and (2) the polynomial demonstrated a cubic component as well.

3.2. Maximal angular displacement (MAD)

Results of RMANOVA revealed a significant height effect ($P = 0.000–0.001$, $F = 336.545–6.631$) for all six of the maximal angular displacements (MAD). Pairwise post hoc analysis of hip flexion and knee flexion exhibited significant differences ($P = 0.000$ in all cases) among all six pairs analyzed. Analysis of ankle dorsiflexion revealed significant differences among all obstacle height pairs except the 31- and 76-mm heights.

Ankle plantarflexion was significantly different among only two pairs; 31- and 126-mm heights ($P = 0.004$, $F = 1.659$), and 76- and 126-mm heights ($P = 0.000$, $F = 26.381$). Knee extension varied significantly among all groups except for 76 and 126 mm ($P = 0.617$, $F = 0.262$). Significant differences among pairs for hip extension values were found for the following pairs of heights: 0 and 76 mm, 0 and 126 mm, and 31 and 126 mm.

All six angular displacements demonstrated a strong linear trend ($P = 0.021–0.000$), while a strong quadratic trend was found in all cases ($P = 0.015–0.000$) except for hip extension values. Additionally, a strong cubic trend was uncovered with respect to knee flexion ($P = 0.001$).

At the ankle the results reflect a functional relationship which is suggestive of a tendency for ankle dorsiflexion to increase with corresponding increases in obstacle height. Increased ankle plantarflexion was adapted as a strategy in stepping over the 126-mm height obstacle. However, increased plantarflexion during the mid-swing or clearance portion of the swing phase is both inefficient and unsafe. More likely this adaptive strategy occurred at some point immediately following clearance and prior to heel contact.

As with toe clearance distance and heel clearance distance, the trend of knee flexion, knee extension, and hip flexion MAD was to increase linearly for the 0-, 31-, and 76-mm obstacles but cease to increase significantly as the height reached the extreme of 126 mm.

3.3. Maximal angular velocity (MAV)

Results of RMANOVA of angular velocities show significant height differences ($P = 0.000$) for all six of the motions analyzed. Post hoc analysis uncovered significant differences among all pairs with regards to ankle dorsiflexion ($P = 0.002–0.000$) and knee flexion ($P = 0.003–0.000$). Analysis of hip flexion ($P = 0.000$) and hip extension ($P = 0.004–0.000$) revealed significant differences in both cases among all groups except between the 76- and 126-mm heights (hip flexion; $P = 0.120$, and hip extension; $P = 0.028$). Knee extension demonstrated significant differences among the 0-mm and both 76- and 126-mm heights, and among the 31-mm and both 76- and 126-mm heights ($P = 0.002–0.000$). Ankle plantarflexion data exhibited significant differences among the 126-mm obstacle and all other heights ($P = 0.003–0.000$), and between the 0- and 76-mm heights ($P = 0.003$).

Trend analysis uncovered a strong linear trend with respect to all angular velocity calculations. A quadratic tendency was seen in the hip flexion and extension data, whereas a cubic trend was noted in the knee flexion and extension calculations.

MAV at the ankle demonstrated a corresponding increase in dorsiflexion and plantarflexion MAV as the height of the obstacle increased. Knee extension, knee flexion, and hip flexion MAV exhibited a leveling off that occurred at the 76- and 126-mm obstacle heights, i.e. a strong linear polynomial trend diminished to create a supplemental polynomial cubic trend.

4. Discussion

Ensuring sufficient clearance of an obstacle during locomotion requires accurate movement and appropriate modifications of the swing limb. In doing so, the locomotor system must attain adequate intersegmental kinematic coordination and control of the swing limb, depending heavily upon the detection of environmental information. The complementary findings with regard to toe and heel clearance distances and angular displacements and velocities of the swing limb while stepping over an obstacle in the path of locomotion suggest a system whose actions may be constrained by the need to ensure both the safety and efficiency of the system.

The emergence of a plateau in toe and heel clearance distances at 126 mm, along with the non-linearity of increases in MAD and MAV, may suggest two similar but separate phenomena. First is the immediate approximation of a critical height which might manifest itself in a distinct transition point at which there is a reversal of the trend of clearance distances from one which is increasing in a linear fashion to a trend which begins to decrease in a linear fashion toward the critical interference point of zero toe or heel clearance (Fig. 2).

The second phenomenon is the onset of a transitional phase following a phase of increasing toe and heel clearance distances. This phase is characterized by invariance in clearance distances which maintain a margin of safety and efficiency. This invariant phase is followed by a trend of linearly decreasing clearance distances until the critical interference point of zero toe or heel clearance distance is reached (Fig. 3).

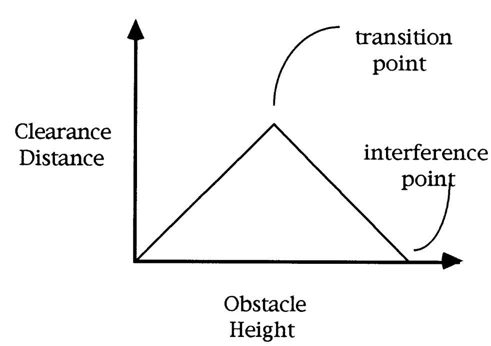

Fig. 2. Distinct transition point in clearance with increasing obstacle height.

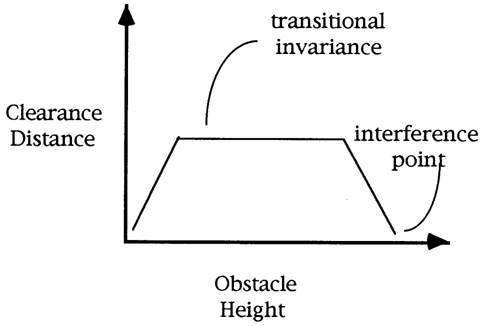

Fig. 3. Gradual transitional phase of invariant clearance distance with increasing obstacle height.

There appear to be four possible phases of clearance distances in stepping over an obstacle: (a) increases with increasing obstacle height; (b) transition phase; either distinct or gradual (invariance of clearance in relation to the height); (c) decreases with increasing obstacle height; and (d) interference (i.e. clearance distance equals zero). In both scenarios, however, the system would likely have reconfigured and changed strategy for the sake of safety and efficiency of movement before reaching the zero distance.

Similarly, the changes in the angular kinematics of the lead swing limb suggest a coordinated and controlled effort to successfully clear the obstacle. In ensuring ample clearance of the obstacle, the requisite functional shortening of the lower extremity was obtained by increasing hip and knee flexion and ankle dorsiflexion [17]. Additionally, increases in knee extension and ankle plantarflexion were seen with increases in obstacle height. However, this most likely occurred after clearance because in early to mid-swing this would result in interference with the object. This was possibly an active, coordinated attempt to rapidly return the swing limb to the ground in order to restore stability to the system [15]. The intersegmental coordination required to achieve successful clearance of the obstacle points to the potential problems facing individuals with arthritic, post-surgical, or post-traumatic joint hypomobility of the lower extremity.

Recent investigations suggest the importance of the angular velocities of the swing limb in the control of locomotion over obstacles [15,17,18]. While Taga [15] spoke of the direct effect of uniarticular flexors at the knee in producing adequate clearance early in swing, Patla and colleagues [17,18] addressed the indirect effect of the biarticular femoral muscles in producing active knee flexion and passive hip flexion and ankle dorsiflexion. Using a simulation model, Armand et al. [18] found that greater hip and knee angular velocities not only affected the elevation of the distal segment, but were essential input parameters for optimizing the solution. Thus it appears plausible that increasing the angular velocity at the knee can produce functional shortening of the limb by acting directly on the knee and indirectly increasing the angular velocity at the hip and ankle.

In conclusion, the overall results depict a task whose critical dynamics seem to emerge quickly during a brief period of time (46–60 ms) following toe off and prior to heel contact. The tendency for linear polynomial trends to be transformed into higher-order polynomial trends as the heights increased was displayed by the toe and heel clearance distances as well as the kinematic properties of the elements responsible for decreasing functional lower extremity length.

The transformation from a linear to non-linear trend occurred consistently at the increase in height from 76 to 126 mm. The implication here may be that a transition in the dynamics essential to clearance of the obstacle emerges from such a change in height. Furthermore, it is likely that the transition in dynamics is an attempt by the system to ensure efficient and safe movement [11,14,16,18]. Thus an increase in height of an obstacle from 76 to 126 mm appears to place the system in a position of greater demand, greater risk, or both, than would an increase from 0 to 31 mm or from 31 to 76 mm. Such information would be helpful in the design of areas with high pedestrian traffic.

This may be an indication that body dimensions (height or lower extremity length) may be constraints on the dynamics of stepping over an obstacle. Furthermore, body dimensions relative to the environment almost certainly relate closely to the constraining factors of safety and efficiency of movement. Although not controlled for in this work, studies have revealed that body dimensions play a significant role in constraining the dynamics of human movement in stairclimbing [23], passage through apertures [24], sitting and stairclimbing [4,25,26].

The role of both toe off distance and heel contact distance are likely to be more important than their invariance may imply. Although toe off distance did not vary significantly with changes in the height of the obstacle, angular velocity increased significantly with increases in the height of the obstacle. It may be that it is not the distance from the obstacle, but rather the time from clearance of the edge of the obstacle. As the height of the obstacle increased, so did the distance from the upper, near edge of the obstacle. This, along with the increase in velocity, may indicate that the system is constrained by time to clearance of the upper edge, rather than the distance of the toe or heel from the obstacle. Investigations into the role of tau, the time to impending contact with or passage through a surface, have shown that temporal constraints on movement are likely to occur [27–36].

Findings with regards to clearance distance in this study are in agreement with those of Chen et al. [10] and Watanabe and Miyakawa [13]. This and related investigations found the clearance distance to increase with a corresponding increase in obstacle height. Chen et al. [10] found foot clearance to increase significantly from the 52-mm object to the 152-mm object, while Watanabe and Miyakawa [13]. reported results which revealed a trend for clearance to plateau as the obstacle height increased from 80 to 120 mm. The results of these three studies did not reveal a significant height effect on either toe off distance or heel contact distance. Although the methods varied slightly these results are also in agreement with the findings of previous studies.

Appendix A. Maximal angular displacement

Subject	Height			
	0 mm, mean (S.D.)	31 mm, mean (S.D.)	76 mm, mean (S.D.)	126 mm, mean (S.D.)
Hip flexion (°)				
1	329.67 (3.76)	343.88 (3.47)	354.72 (2.66)	360.18 (0.50)
2	319.26 (1.60)	331.47 (0.80	343.34 (2.05	350.44 (2.28)
3	309.16 (1.09)	319.52 (1.31)	333.72 (2.05)	341.23 (4.68)
4	308.38 (1.50)	322.45 (3.77)	335.07 (3.94)	338.48 (1.36)
5	315.83 (2.15)	321.81 (1.88)	330.17 (2.71)	337.14 (2.77)
6	310.45 (1.96)	325.44 (3.22)	336.34 (1.91)	340.05 (3.56)
7	308.72 (1.56)	321.76 (3.70)	331.56 (6.39)	339.04 (1.20)
8	315.84 (0.49)	324.49 (2.56)	330.49 (1.57)	339.17 (2.40)
9	301.70 (5.06)	312.42 (5.42)	319.82 (2.64)	326.66 (2.17)
10	302.30 (2.48)	310.71 (6.10)	323.71 (3.62)	328.54 (5.60)
11	317.39 (8.32)	321.47 (0.41)	335.84 (3.14)	341.71 (2.11)
12	322.77 (3.05)	333.69 (2.02)	339.55 (2.22)	347.12 (0.28)
13	312.60 (1.20)	323.78 (2.67)	329.71 (0.80)	338.36 (1.43)
14	316.60 (1.32)	332.69 (1.38)	349.91 (3.39)	355.07 (0.70)
15	299.32 (2.11)	309.67 (2.48)	319.21 (0.55)	324.04 (1.45)
Hip extension (°)				
1	305.99 (1.37)	304.46 (1.93)	303.37 (2.18)	305.16 (2.35)
2	285.71 (1.95)	288.48 (2.91)	291.88 (3.99)	291.77 (0.85)
3	273.92 (1.48)	273.87 (6.31)	278.78 (5.66)	276.01 (1.25)
4	282.89 (1.78)	279.19 (2.33)	280.18 (2.22)	279.73 (3.16)
5	284.80 (1.13)	287.91 (1.44)	284.58 (3.38)	288.63 (2.24)
6	280.36 (1.90)	281.43 (1.10)	282.85 (1.33)	281.71 (0.30)
7	282.89 (1.62)	278.78 (4.25)	286.76 (0.16)	284.03 (1.28)
8	292.08 (1.41)	292.17 (0.85)	294.16 (1.88)	293.26 (2.80)
9	275.15 (5.04)	278.52 (1.39)	277.41 (2.05)	277.40 (1.12)
10	277.15 (5.12)	278.71 (0.67)	279.27 (2.77)	279.00 (2.81)
11	275.36 (0.99)	277.04 (4.87)	277.05 (1.66)	280.05 (1.94)
12	284.30 (1.59)	284.10 (2.27)	287.39 (1.12)	287.27 (1.11)
13	279.98 (0.06)	280.99 (0.73)	284.38 (1.27)	282.04 (2.19)
14	282.67 (1.28)	285.26 (0.89)	283.18 (2.09)	288.89 (1.76)
15	269.39 (2.78)	271.07 (1.62)	273.03 (2.37)	271.03 (1.71)
Knee flexion (°)				
1	97.80 (1.09)	82.14 (0.32)	68.35 (1.37)	62.49 (0.38
2	105.31 (2.09)	92.44 (3.11)	81.93 (4.80)	71.28 (2.40)
3	105.43 (1.98)	91.44 (2.75)	73.98 (1.26)	67.20 (2.14)
4	104.54 (1.46)	88.04 (5.35)	66.15 (0.66)	61.68 (5.00)

5	97.99 (3.77)	89.01 (1.77)	78.92 (3.43)	71.51 (0.92)
6	113.25 (2.50)	95.97 (3.53)	79.49 (7.29)	75.96 (2.69)
7	111.33 (1.37)	93.21 (8.28)	77.48 (6.61)	68.59 (2.61)
8	107.33 (0.94)	92.63 (2.01)	83.56 (0.98)	78.83 (2.29)
9	117.98 (1.21)	108.73 (2.41)	91.98 (0.52)	85.56 (1.02)
10	109.64 (3.45)	100.58 (2.15)	83.78 (4.02)	68.82 (6.39)
11	106.73 (2.65)	101.08 (1.21)	83.35 (4.27)	73.62 (0.92)
12	99.51 (0.71)	86.64 (3.25)	76.22 (5.24)	67.93 (1.73)
13	105.15 (2.44)	90.58 (0.98)	73.28 (1.87)	62.55 (0.40)
14	109.14 (1.95)	85.44 (2.01)	63.53 (1.24)	58.49 (3.00)
15	112.09 (2.30)	98.52 (2.28)	84.68 (0.19)	79.93 (1.92)
Knee extension (°)				
1	172.42 (1.49)	164.19 (1.19)	162.84 (0.93)	159.25 (1.78)
2	179.02 (3.34)	169.84 (3.60)	165.78 (1.70)	164.50 (0.38)
3	176.54 (0.84)	172.75 (2.22)	169.16 (3.27)	171.91 (0.83)
4	175.25 (3.90)	165.85 (2.10)	160.47 (7.15)	160.76 (7.02)
5	179.55 (1.92)	175.39 (2.09)	172.25 (3.56)	173.99 (1.09)
6	184.68 (0.67)	180.56 (3.65)	179.38 (1.21)	182.26 (3.72)
7	179.90 (0.94)	173.71 (6.39)	168.26 (2.06)	166.44 (3.81)
8	182.92 (0.84)	180.03 (1.42)	178.65 (1.67)	177.57 (1.34)
9	178.91 (1.26)	174.91 (1.34)	175.22 (1.17)	173.60 (1.90)
10	171.92 (1.73)	167.29 (0.90)	163.13 (0.95)	161.89 (1.42)
11	180.79 (1.28)	180.51 (1.06)	173.19 (0.07)	171.04 (1.94)
12	176.61 (1.68)	171.62 (2.21)	167.15 (3.39)	171.40 (1.89)
13	177.91 (0.70)	174.68 (1.51)	172.48 (1.62)	174.14 (1.47)
14	175.04 (0.92)	167.04 (4.74)	162.96 (3.69)	163.95 (1.64)
15	181.17 (0.64)	177.36 (2.50)	168.73 (1.30)	171.71 (4.15)
Ankle dorsiflexion (°)				
1	276.15 (2.21)	281.26 (3.65)	283.05 (2.77)	284.88 (2.80)
2	271.38 (1.44)	280.65 (6.31)	280.45 (3.98)	284.64 (2.66)
3	276.84 (0.40)	276.81 (0.62)	281.17 (2.46)	281.27 (1.69)
4	277.28 (1.73)	289.02 (1.67)	286.01 (3.75)	286.93 (0.42)
5	271.96 (2.45)	274.23 (0.52)	279.70 (2.03)	278.87 (0.50)
6	269.54 (1.75)	273.86 (3.85)	271.37 (4.57)	274.35 (2.65)
7	270.06 (0.57)	273.07 (3.33)	277.45 (1.97)	274.83 (0.51)
8	270.84 (0.66)	277.43 (1.65)	282.45 (1.78)	288.30 (3.28)
9	283.98 (0.88)	284.20 (1.08)	284.75 (3.57)	290.51 (0.81)
10	278.82 (3.72)	286.91 (1.14)	292.76 (2.75)	294.22 (0.53)
11	268.93 (1.61)	270.56 (2.46)	274.87 (3.90)	278.31 (1.06)
12	269.65 (4.10)	276.96 (0.30)	276.47 (1.48)	276.87 (0.40)
13	273.31 (0.21)	278.80 (0.22)	283.95 (1.51)	283.12 (2.60)
14	275.99 (0.90)	281.37 (1.71)	281.28 (2.42)	284.94 (2.34)
15	277.95 (3.72)	282.51 (1.18)	279.82 (2.52)	285.07 (1.82)
Ankle plantarflexion (°)				
1	245.39 (1.81)	247.21 (1.12)	234.00 (4.31)	232.57 (0.76)
2	236.10 (1.65)	236.23 (5.95)	235.49 (3.41)	232.47 (1.66)
3	245.94 (2.03)	248.40 (1.62)	245.18 (4.28)	237.96 (2.53)
4	250.69 (2.72)	252.93 (5.49)	251.65 (2.14)	248.32 (4.91)
5	250.74 (2.26)	252.80 (1.26)	254.77 (1.85)	254.73 (1.78)
6	239.33 (0.32)	243.87 (3.01)	229.63 (2.37)	225.30 (1.54)
7	246.25 (2.49)	242.37 (5.47)	236.78 (1.98)	231.73 (2.47)

8	247.29 (0.28)	251.59 (1.44)	256.11 (0.31)	257.16 (1.70)
9	261.70 (4.22)	264.31 (0.39)	266.46 (1.15)	265.48 (3.12)
10	254.41 (1.59)	258.51 (2.20)	258.28 (1.52)	256.21 (2.92)
11	236.07 (2.24)	233.67 (4.08)	229.67 (1.25)	225.05 (1.63)
12	239.56 (2.09)	237.11 (0.45)	236.61 (2.73)	234.19 (1.17)
13	243.18 (1.38)	245.19 (0.42)	244.45 (3.41)	241.65 (5.71)
14	249.43 (1.70)	242.36 (2.57)	240.19 (1.08)	238.61 (2.38)
15	251.98 (3.29)	254.95 (1.64)	243.31 (1.35)	239.82 (3.96)

Appendix B. Maximal angular velocity

Subject	Height			
	0 mm, mean (S.D.)	31 mm, mean (S.D.)	76 mm, mean (S.D.)	126 mm, mean (S.D.)
Hip flexion (°/s)				
1	175.63 (21.04)	211.43 (16.85)	247.03 (69.73)	273.00 (46.19)
2	209.13 (47.27)	291.37 (80.76)	333.37 (68.28)	276.27 (18.81)
3	208.10 (5.92)	271.50 (63.57)	281.20 (28.66)	332.10 (48.40)
4	152.83 (14.53)	196.57 (34.00)	268.93 (57.33)	244.70 (5.98)
5	167.30 (9.75)	194.73 (28.22)	236.17 (3.32)	252.67 (3.47)
6	182.97 (9.54)	218.73 (18.01)	264.13 (14.31)	263.37 (9.55)
7	154.77 (28.69)	205.87 (24.77)	279.60 (53.22)	284.87 (45.73)
8	167.07 (13.04)	195.43 (2.72)	221.33 (9.91)	240.10 (14.05)
9	167.47 (34.62)	182.27 (13.31)	206.57 (29.41)	251.23 (15.76)
10	160.93 (23.76)	202.40 (28.35)	262.37 (31.75)	238.60 (46.31)
11	242.40 (23.94)	254.70 (28.80)	320.53 (11.66)	332.67 (10.10)
12	220.47 (4.05)	269.93 (33.42)	319.43 (12.16)	364.03 (40.09)
13	212.07 (29.71)	232.50 (31.97)	307.43 (15.77)	309.47 (39.76)
14	211.07 (9.31)	309.17 (48.90)	326.67 (37.89)	358.77 (23.56)
15	158.90 (22.97)	200.17 (9.60)	228.90 (15.77)	282.63 (48.40)
Hip extension (°/s)				
1	61.93 (45.87)	125.83 (23.19)	227.20 (64.90)	186.43 (30.27)
2	55.57 (14.26)	128.90 (9.07)	166.13 (47.75)	196.40 (58.07)
3	60.80 (32.01)	97.60 (39.09)	111.17 (19.89)	322.07 (49.91)
4	26.37 (28.49)	99.70 (27.28)	174.60 (22.46)	199.53 (41.57)
5	90.93 (9.91)	117.43 (12.79)	142.63 (13.32)	157.30 (8.56)
6	84.90 (22.77)	124.00 (27.15)	150.00 (35.61)	184.00 (7.39)
7	41.80 (12.80)	119.50 (9.13)	123.87 (28.79)	153.13 (40.07)
8	86.47 (5.40)	142.57 (38.36)	146.67 (22.42)	152.87 (40.25)
9	25.13 (29.46)	57.93 (34.69)	135.87 (45.24)	190.20 (27.73)
10	76.53 (13.60)	80.63 (42.74)	153.77 (27.89)	177.27 (36.13)
11	135.53 (55.25)	140.87 (26.99)	217.43 (26.62)	248.47 (13.14)
12	119.67 (63.93)	178.53 (12.11)	184.67 (17.88)	249.53 (38.75)
13	120.20 (6.88)	232.20 (36.43)	217.57 (29.73)	230.20 (26.63)
14	64.53 (35.47)	156.60 (3.21)	247.37 (41.64)	253.43 (35.88)
15	49.83 (51.78)	166.87 (42.31)	158.37 (8.26)	160.57 (4.74)

Knee flexion (°/s)

1	333.97 (9.77)	384.93 (12.68)	445.77 (25.08)	434.63 (32.05)
2	472.93 (34.98)	535.27 (28.49)	554.03 (66.52)	587.57 (19.93)
3	372.60 (26.13)	443.10 (19.35)	549.20 (12.89)	554.07 (27.79)
4	319.47 (24.42)	399.07 (31.47)	427.17 (41.92)	467.07 (31.75)
5	347.00 (22.97)	377.60 (6.45)	398.37 (19.84)	384.47 (51.36)
6	355.87 (18.15)	445.73 (12.91)	501.07 (42.42)	497.23 (20.77)
7	354.17 (17.86)	456.53 (59.42)	494.73 (20.24)	532.07 (30.86)
8	377.50 (73.93)	388.60 (7.62)	427.93 (9.47)	454.73 (31.38)
9	281.77 (9.03)	306.17 (17.08)	373.03 (14.60)	412.00 (12.85)
10	351.70 (9.13)	367.87 (8.46)	417.57 (12.17)	464.43 (35.69)
11	485.80 (54.54)	449.03 (21.25)	537.30 (12.47)	557.13 (1.88)
12	434.07 (24.87)	506.93 (25.88)	573.20 (49.12)	594.83 (14.38)
13	415.93 (26.50)	466.57 (1.72)	534.50 (10.38)	599.70 (13.80)
14	445.50 (6.94)	499.63 (14.43)	556.93 (37.91)	554.63 (34.90)
15	346.40 (11.55)	409.70 (2.13)	452.20 (13.33)	472.20 (25.42)

Knee extension (°/s)

1	422.53 (19.30)	422.60 (21.45)	475.17 (11.02)	469.10 (36.45)
2	475.67 (44.48)	463.03 (17.19)	464.63 (60.19)	513.57 (15.46)
3	435.50 (11.94)	420.93 (21.75)	456.57 (31.72)	485.77 (15.13)
4	366.23 (14.57)	384.93 (38.51)	511.33 (21.55)	516.57 (71.52)
5	414.30 (16.31)	401.73 (19.83)	440.80 (11.55)	418.60 (7.13)
6	446.83 (18.48)	398.70 (39.33)	410.90 (65.19)	423.80 (54.79)
7	388.13 (9.32)	440.33 (24.69)	452.53 (21.88)	457.40 (10.09)
8	416.73 (84.15)	469.57 (14.16)	493.47 (12.27)	447.93 (21.51)
9	320.10 (16.21)	305.27 (7.79)	413.67 (20.23)	413.70 (3.33)
10	405.77 (32.53)	377.13 (43.06)	436.93 (10.13)	484.67 (39.87)
11	487.47 (84.35)	437.87 (35.71)	477.60 (18.70)	562.27 (9.18)
12	474.27 (39.90)	497.07 (7.98)	501.93 (89.39)	572.50 (26.31)
13	468.00 (6.81)	483.27 (20.31)	527.87 (32.07)	561.10 (44.53)
14	443.13 (27.24)	493.43 (24.68)	550.47 (20.03)	556.43 (47.14)
15	423.33 (16.11)	405.17 (12.72)	476.23 (18.21)	474.93 (22.55)

Ankle dorsiflexion (°/s)

1	209.27 (41.36)	265.83 (20.50)	376.27 (90.83)	481.80 (17.99)
2	244.10 (21.90)	351.70 (43.14)	379.33 (43.64)	382.47 (11.76)
3	190.60 (4.84)	228.17 (30.87)	292.77 (95.91)	371.97 (14.00)
4	193.47 (10.87)	241.17 (59.03)	292.90 (67.41)	380.80 (45.82)
5	151.90 (20.82)	152.63 (15.26)	162.60 (20.66)	159.30 (11.34)
6	196.97 (19.23)	234.57 (59.77)	319.03 (94.49)	354.43 (37.67)
7	165.20 (18.71)	294.80 (83.80)	386.23 (95.77)	457.23 (10.48)
8	204.13 (18.15)	247.20 (10.55)	207.50 (12.55)	228.53 (70.96)
9	161.70 (29.12)	165.50 (9.42)	181.90 (15.55)	200.30 (25.40)
10	192.03 (20.62)	219.20 (34.73)	212.43 (31.90)	230.47 (82.02)
11	244.47 (14.51)	303.40 (55.54)	424.33 (29.48)	506.90 (44.69)
12	258.50 (51.23)	317.50 (46.83)	353.77 (44.66)	360.43 (13.32)
13	246.10 (6.28)	291.77 (18.71)	332.90 (25.03)	342.40 (41.39)
14	171.97 (10.55)	277.47 (27.99)	293.57 (44.13)	375.90 (20.82)
15	200.37 (38.61)	218.57 (4.66)	354.93 (22.14)	381.60 (18.50)

Ankle plantarflexion (°/s)

1	211.70 (42.08)	237.83 (60.41)	388.73 (68.61)	396.13 (69.23)

2	252.00 (52.32)	382.60 (61.90)	395.83 (41.76)	444.90 (32.20)
3	161.23 (15.64)	186.80 (51.45)	258.67 (93.52)	339.77 (35.59)
4	182.67 (42.95)	246.10 (86.91)	244.77 (23.11)	297.63 (10.70)
5	206.43 (24.30)	116.70 (19.75)	175.40 (31.28)	139.73 (28.96)
6	217.07 (78.36)	266.60 (92.92)	243.67 (20.51)	285.53 (41.50)
7	170.23 (56.55)	235.37 (41.09)	268.47 (39.46)	244.47 (12.54)
8	141.80 (25.15)	189.90 (22.32)	147.60 (19.76)	194.17 (16.60)
9	163.73 (83.53)	120.33 (32.28)	143.27 (36.03)	204.67 (41.86)
10	109.03 (58.05)	119.17 (12.19)	348.20 (25.92)	372.17 (44.36)
11	257.83 (51.66)	292.07 (55.85)	359.77 (69.64)	415.43 (33.36)
12	226.13 (22.91)	168.33 (12.00)	201.00 (87.79)	362.83 (75.00)
13	148.53 (40.49)	154.67 (43.05)	141.93 (7.61)	168.50 (6.08)
14	114.10 (54.04)	334.17 (52.24)	265.17 (46.02)	297.80 (14.41)
15	123.13 (50.02)	159.57 (23.74)	286.50 (18.74)	333.77 (45.19)

Appendix C. Distance

Subject	Height			
	0 mm, mean (S.D.)	31 mm, mean (S.D.)	76 mm, mean (S.D.)	126 mm, mean (S.D.)
Toe-off (m)				
1	1.046 (0.020)	1.048 (0.019)	1.015 (0.034)	1.049 (0.042)
2	0.876 (0.140)	0.841 (0.079)	0.848 (0.130)	0.773 (0.021)
3	0.997 (0.067)	0.928 (0.037)	0.960 (0.037)	0.967 (0.044)
4	0.927 (0.034)	0.949 (0.034)	0.897 (.007)	0.916 (0.033)
5	0.765 (0.025)	0.769 (0.032)	0.729 (0.021)	0.729 (0.036)
6	0.871 (0.038)	0.894 (0.012)	0.905 (0.035)	0.879 (0.049)
7	0.909 (0.100)	0.875 (0.072)	0.852 (0.045)	0.873 (0.042)
8	0.651 (0.013)	0.676 (0.034)	0.672 (0.030)	0.717 (0.050)
9	0.775 (0.034)	0.783 (0.026)	0.706 (0.039)	0.777 (0.014)
10	0.626 (0.027)	0.620 (0.008)	0.665 (0.027)	0.657 (0.026)
11	1.017 (0.041)	1.015 (0.028)	1.005 (0.027)	1.009 (0.044)
12	1.109 (0.007)	1.126 (0.047)	1.064 (0.015)	1.099 (0.034)
13	0.735 (0.050)	0.756 (0.014)	0.760 (0.011)	0.823 (0.031)
14	0.797 (0.022)	0.796 (0.016)	0.812 (0.016)	0.778 (0.040)
15	0.843 (0.051)	0.806 (0.024)	0.765 (0.044)	0.827 (0.045)
Toe clearance (m)				
1	0.059 (0.008)	0.111 (0.003)	0.183 (0.005)	0.181 (0.011)
2	0.063 (0.004)	0.114 (0.008)	0.148 (0.018)	0.161 (0.005)
3	0.066 (0.014)	0.106 (0.017)	0.161 (0.011)	0.169 (0.014)
4	0.058 (0.005)	0.118 (0.022)	0.171 (0.012)	0.157 (0.006)
5	0.092 (0.025)	0.114 (0.027)	0.133 (0.006)	0.145 (0.011)
6	0.059 (0.019)	0.109 (0.009)	0.181 (0.003)	0.180 (0.020)
7	0.056 (0.006)	0.102 (0.035)	0.162 (0.042)	0.184 (0.014)
8	0.073 (0.006)	0.115 (0.002)	0.137 (0.011)	0.133 (0.008)
9	0.059 (0.004)	0.072 (0.010)	0.117 (0.002)	0.116 (0.007)
10	0.082 (0.005)	0.094 (0.011)	0.133 (0.007)	0.168 (0.029)

11	0.108 (0.043)	0.094 (0.011)	0.156 (0.010)	0.175 (0.006)
12	0.062 (0.002)	0.100 (0.006)	0.113 (0.010)	0.120 (0.006)
13	0.065 (0.011)	0.081 (0.013)	0.119 (0.004)	0.129 (0.007)
14	0.065 (0.002)	0.132 (0.005)	0.202 (0.010)	0.203 (0.011)
15	0.061 (0.003)	0.098 (0.015)	0.131 (0.009)	0.129 (0.018)
Heel clearance (m)				
1	0.050 (0.008)	0.088 (0.009)	0.151 (0.010)	0.149 (0.016)
2	0.057 (0.007)	0.094 (0.005)	0.117 (0.018)	0.139 (0.010)
3	0.059 (0.008)	0.098 (0.022)	0.143 (0.001)	0.139 (0.007)
4	0.040 (0.008)	0.073 (0.020)	0.128 (0.011)	0.096 (0.006)
5	0.076 (0.016)	0.073 (0.005)	0.084 (0.001)	0.083 (0.008)
6	0.060 (0.006)	0.091 (0.018)	0.151 (0.009)	0.149 (0.032)
7	0.053 (0.005)	0.091 (0.044)	0.139 (0.041)	0.168 (0.016)
8	0.081 (0.006)	0.096 (0.005)	0.113 (0.011)	0.111 (0.014)
9	0.050 (0.010)	0.051 (0.010)	0.086 (0.006)	0.083 (0.011)
10	0.074 (0.014)	0.077 (0.010)	0.107 (0.004)	0.127 (0.027)
11	0.097 (0.039)	0.096 (0.017)	0.153 (0.006)	0.168 (0.002)
12	0.066 (0.009)	0.082 (0.011)	0.103 (0.007)	0.106 (0.006)
13	0.071 (0.008)	0.078 (0.012)	0.101 (0.010)	0.104 (0.013)
14	0.058 (0.003)	0.120 (0.006)	0.179 (0.008)	0.176 (0.002)
15	0.050 (0.011)	0.077 (0.021)	0.123 (0.007)	0.109 (0.021)
Heel contact (m)				
1	0.220 (0.017)	0.262 (0.043)	0.298 (0.044)	0.304 (0.028)
2	0.230 (0.068)	0.235 (0.032)	0.226 (0.053)	0.278 (0.012)
3	0.288 (0.032)	0.390 (0.034)	0.357 (0.031)	0.330 (0.038)
4	0.099 (0.011)	0.182 (0.020)	0.217 (0.014)	0.206 (0.034)
5	0.245 (0.041)	0.227 (0.006)	0.248 (0.013)	0.245 (0.018)
6	0.214 (0.023)	0.225 (0.059)	0.230 (0.009)	0.229 (0.042)
7	0.218 (0.076)	0.214 (0.059)	0.255 (0.021)	0.277 (0.029)
8	0.410 (0.007)	0.359 (0.015)	0.380 (0.003)	0.399 (0.017)
9	0.316 (0.024)	0.272 (0.032)	0.334 (0.023)	0.290 (0.024)
10	0.268 (0.046)	0.251 (0.005)	0.269 (0.035)	0.273 (0.009)
11	0.306 (0.019)	0.135 (0.013)	0.308 (0.033)	0.287 (0.047)
12	0.292 (0.030)	0.343 (0.009)	0.380 (0.046)	0.347 (0.006)
13	0.383 (0.020)	0.377 (0.009)	0.369 (0.011)	0.367 (0.012)
14	0.270 (0.029)	0.287 (0.026)	0.276 (0.008)	0.295 (0.032)
15	0.214 (0.062)	0.261 (0.044)	0.291 (0.017)	0.262 (0.020)

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