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A common perceptual parameter for stair climbing for children, young and old adults

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Abstract

In this paper we examine whether a common perceptual parameter is available for guiding old adults, young adults and children in climbing the highest stair mountable in a bipedal fashion. Previous works have shown that the ratio between the height of the stair and the hip height was the body-scaled invariance adopted as information for selecting the highest stair by young adults [Journal of Experimental Psychology: Human Perception and Performance 10 (1984) 683–703] but not by older adults [Journal of Experimental Psychology: Human Perception and Performance 3 (1992) 691–697]. Indeed, for older adults additional bio-mechanical parameters needed to be added to the model due to their decrease in leg strength and flexibility.

Up to now, no perceptual invariant has been identified yet for determining the relevant information used for guiding the stair climbing action for normal healthy people. We propose a new parameter as the angle defined by the ratio between the height of the stair and the distance taken from the feet to the top edge of the stair before the initiation of the movement. We show that this angle is the same for children, young adults and older adults despite the different kinematics of the motion, the anthropometrics and the skill ability exhibit by the participants. In summary we show that even when the climbability judgments, based on the simple ratio leg length-stair height, are influenced by differences in age, participants use a common perceptual variable when they are coordinating their stair climbing action.

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1. Introduction

Over the last few years there has been a great interest in perception–action capabilities in climbing stairs, since this represents one of the basic actions in everyday life. Interest has been devoted to normal population (Warren, 1984) and then to special populations as well, such as old adults (Konczak, Meeuwssen, & Cress, 1992) and children (Adolph, Eppler, & Gibson, 1993), in order to understand how the perception–action capability of this activity changes during life span.

Following the seminal work associated with the ecological approach (Gibson, 1979), animals are thought to visually guide their behavior by perceiving what action possibilities are offered by the environment. Gibson defined the information in this relationship between an organism and its environment as an “affordance”; thus if an animal guides its activity by perceiving affordances, it must be capable of perceiving the relationship between environmental properties and the properties of its own action system. One of the implications of this assumption is that actions are “body-scaled” and perceptions are driven by intrinsic body measures as opposed to extrinsic or absolute measures. Both the action system as well as the environmental measures may be described by geometric variables, such as object size and body dimensions (Cesari & Newell, 1999, 2000), and/or by kinetic and kinematics variables (McMahon, 1984; Pierrynowski & Galea, 2001; Rome, 1992).

For the visual guidance of activity to be successful, the perceiver must be capable of identifying the limits of action and, then selecting the most efficient path for the action. The perceptual category boundaries correspond to critical values and, according to the similarity hypothesis, these values are constant over the scale changes in the system (McMahon & Bonner, 1983). One important implication for the hypothesized relationship between perception and action is that predictions can be made from an analysis of action to define perception and vice versa.

In stair climbing the environmental measures that the perceiver needs to take into account are the stair dimensions. Stairs offer different heights: from the deep step with low riser height, as typically found in public buildings, to the shallow step with height, as typically found in basements and attics. By the same token, people have different anthropometric measures which change within the individual’s life span. The point is that climbers need to be ready to approach different stair sizes at any moment in their life. How is it that they can obtain relevant information about the stair size to adjust their movements? Several researchers have focused on the identification of invariant ratios between slopes and/or stairs and body dimensions. These studies have focused on adults (Mark, 1987; Mark & Vogele, 1987; Warren, 1984), on infants and young children (Adolph et al., 1993; Ulrich, Thelen, & Niles, 1990), and on old adults (Konczak et al., 1992).

Warren (1984) found that for young adults the geometric ratio between riser height and leg length was the same despite differences in body size. In his experiment, all the participants, both tall and short, perceived a stair to be no longer climbable in a bipedal fashion, when the riser height of the stair exceeded 88% of their leg length. Warren anticipated that his model could not be generalized to other populations such as old adults. Indeed when old adults were tested, they did not show the same

maximum stair height to leg length ratio as did the young (Konczak et al., 1992). This difference was interpreted as being the result of their decrease of strength and joint flexibility. Moreover, Meeuwssen (1991) found a significant difference in this ratio between young females with high joint flexibility, and young females with low joint flexibility, both for selected as well as climbed stairs. The main limitation of all of previous works is that it does not provide a common scaling law that can describe how healthy people of different ages and different motor skill, select and climb the critical riser height of a stair. The question we asked in this experiment is whether a common perceptual information in guiding and controlling this action exists for climbers. In other words, we tested the possibility that even when the climbability judgments are influenced by differences in for instance age, strength, and flexibility, participants may still use a common perceptual variable when they are coordinating their stair climbing movements.

In order to test our hypothesis participants had to select and then climb the stair selected. We found that all of them, despite differences in anthropometrics and skill, were using the same parameter for guiding the action. We identified the parameter as the angle α defined by the ratio between the height of the stair and the distance from the feet to the top of the stair before the initiation of movement. Since α was invariant across the participants, we claim that α is a parameter used as perceptual information for guiding participants in climbing the critical height of a stair. In addition, the kinematics of the motion were examined to measure the movement time and joint angles. In summary, we demonstrate that different actions can be applied to accomplish the task while using the same relevant perceptual information.

2. Methods

2.1. Participants

The volunteers that participated in this study consisted of: 13 older adults (age \underline{M} = 60.8, SD = 6.4, and leg length \underline{M} = 77.7, SD = 5.9 cm); 13 young adults (age \underline{M} = 21.2, SD = 2, and leg length \underline{M} = 78.5, SD = 2.4 cm); and 13 children (age \underline{M} = 6.7, SD = 1.7, and leg length \underline{M} = 57.7, SD = 7.7 cm). Informed written consent was obtained from all participants. None of the participants had injuries or illnesses which would have influenced the results of the experiments. Before entering the laboratory the participants had no information about the experiment.

3. Anthropometrics

The following anthropometric measures were obtained for each participant: total standing height, eye height, sitting height (from the hips to the top of the head), total leg length. To measure the sitting height we asked participants to be seated on an adjustable chair such that their hips and knees joints were flexed at 90°. A tape was attached to the back of the chair to measure the distance between the seat

and the top of the participant's head. The total leg length was calculated by subtracting standing height from sitting height (Warren, 1984). For each measurement we considered the mean of three trials.

3.1. Data collection

Kinematics data was collected with an ELITE system (BTS) using 4 infrared cameras operating at 100 Hz. A fourth order and zero lag low pass Butterworth filter with a cut off frequency of 4 Hz was used. The cameras were placed sagittally with respect to the participant. Reflective markers were placed on the following anthropometric landmarks of one side of the body: 5th metatarsal head, heel, lateral malleolus, lateral epicondyle, and great trochanter, defining the segments foot, shank, and thigh. The dominant side was defined as the leg which was used to take the first step up to the stair.

3.2. Procedures

The experiment took place in a room 15 m long, 8 m wide and 4 m high. 18 stairs made of wood (pine) and not painted were used in the experiment. They were 50 cm wide, 50 cm deep and the riser heights ranged from 10 to 90 cm with an increment of 5 cm between each stair. Participants were tested individually. The stairs were arranged in a semicircle in a decreasing order of the height of the stairs and the participants, standing at 2 m distance from them, were asked to identify the one with the greatest riser height they thought they could climb without outside support or using their hands. The riser height of the selected stair was recorded as the perceived maximum riser height. Then the second part of the experiment, namely the actual climbing of the stair, followed. The stair selected by the participant was placed in front of him/her at a distance of 4 m. For each trial, the participant was asked to walk toward the stair and then stop and stand still with feet parallel ready to climb the stair. It was emphasized that from the stationary position, participant needed to perform a direct step on the stair and that no extra walk was allowed. The participant attempted to climb the same stair three times. The first stair that participant was asked to climb was the one that measured 10 cm below the chosen one. Afterwards the stair was replaced by the next higher one (plus 5 cm) until the critical height was reached and the participant was not able to climb the stair without the help of the hands. No reaction time or motion speed was required.

We used the texture of the floor made of lines 2.5 cm apart from each other, as a ruler for measuring the distance that each participant took in each trial from the stair while standing still. Precisely the distance measured was from the participants' feet to the bottom of the stair. No instruction was given to the participant about the distance to take. Each participant chose spontaneously where to stand before the actual initiation of the movement. The same instruction was given to the participants following a fixed protocol.

Before the experiment was performed, a flexibility test took place: the participant was asked while standing to flex the knee and then rise the shank as much as possible

without the help of the hands. The maximum closure of the hip joint angle was then calculated and considered as a parameter for individual joint flexibility.

4. Data analysis

All comparisons among the three groups (children, old and young adults) were performed by applying a one-way between-subjects analysis of variance (ANOVA), the significant p -value was set at 0.05. A follow-up test, using the Tukey HSD procedure was applied. For the kinematics data where two groups were compared (old and young adults), we applied a paired t -test, the significant p -value was set at 0.05.

5. Results

The first step for the analysis was to compare the anthropometrical measures across the three populations. Leg length and eye height ANOVAs were significant for both variables, for leg length: $F(2, 36) = 46.8$, and for eye height: $F(2, 36) = 86.9$. Follow-up tests indicated that the leg length and the eye height were the same for young and older adults while both the adults groups differed from children. We then compared the height of the stair selected and the height of the stair climbed across the three groups. Both the ANOVAs performed reached significance: for the stair perceived $F(2, 36) = 41.13$ and for the stair climbed: $F(2, 36) = 66.2$. Post hoc tests revealed that the heights of the stairs climbed and perceived were different for young adults compared to children and old adults (Table 1).

We normalized the height of stair perceived for each participant for their leg length. The ANOVA for the body scaled height of the stair perceived was significant $F(2, 36) = 20.53$. The post hoc test revealed no difference between young adults and children but a difference between these two groups and old adults. This means that the perception of the critical stair was similarly scaled for young adults and children

Table 1
Leg length, height achieved and perceived scaled and not scaled

Group	Leg length (cm)	Achieved (cm)	Perceived (cm)	Achieved/ L_L	Perceived/ L_L
<i>Young adults</i>					
<i>M</i>	78.5	79.2	72.7	1	0.93
<i>SD</i>	2.4	4.4	4.8	0.05	0.06
<i>Older adults</i>					
<i>M</i>	77.7	57.7	52.3	0.74	0.67
<i>SD</i>	5.9	6.9	6.3	0.07	0.06
<i>Children</i>					
<i>M</i>	59	52.6	50.7	0.89	0.88
<i>SD</i>	7.7	6.9	8.8	0.07	0.15

while it was differently scaled for older adults. Young adults perceived the critical stair to be in the mean 93% of their leg length and children perceived the critical stair to be 88% of their leg length. In contrast, old adults perceived the critical stair to be 67% of their leg length. The ANOVA for the stair actually climbed was significant: $F(2, 36) = 48.31$ and the post hoc test revealed that the three groups differed. More specifically, the young adults climbed stairs on average 100% of their leg length, children 89% of their leg length and older adults 74% of their leg length (see Table 1).

The large majority of the participants underestimated their ability to climb a stair, in the mean by about 6 cm. In particular, for young adults 7% overestimated his performance, 15% matched the measure of the stair and 76% underestimated their performance; for older adults 46% matched the measure of the stairs while 53% underestimated their performance; for children the situation was more variable in that 30% matched the measure of the stairs, 23% overestimated their ability to climb the critical stair and 46% underestimated. In general the old adults were the most precise with a mean error of 5.2 cm, while the mean error for children and young adults was respectively 6 and 7.3 cm. It is important to notice that in the previous work (Konczak et al., 1992) the riser increment between stairs was bigger than the one used in this experiment (7.5 cm), and young adults presented less precision than old adults with a mean error of 7.5 cm.

To summarize the results and compare them to previous work, young adults and children selected the critical stair at a ratio which was above 88% of their leg length as Warren predicted (1984) while older adults climbed the critical stair at a significantly lower percentage of leg-length when compared to children and young adults, replicating Konczak et al. (1992) results. In addition, old adults presented more precision in selecting the stairs compared to children and young adults.

The explanation that older adults do not use the same body-scaled parameters as younger adults and children due to their decrease in force and flexibility (Konczak et al., 1992) leaves open an important question: is there a common perceptual guidance available for climbing stairs for children, young and old adults? When searching for a relevant action variable in stair climbing, the bio-mechanical and physiological constraints certainly affect performance and need to be taken into consideration. A simple description of the motion can be summarized in two main steps: first the climber needs to place the stepping foot onto the stair surface (step-phase), then he/she needs to move the center of mass over this newly placed foot (push phase) and finally extend the leg. During the step phase climbers have to move the stepping leg upward while controlling balance with the supporting leg. In order to accomplish this task it is important that the stepping foot does not hit the stair while reaching the top. In this case, the distance taken by the participant from the stair before the initiation of the motion depends mainly on the level of flexibility expressed by the individual, particularly at the hip joint. For the second phase of the motion, the pushing phase, the climber needs to be able to apply force downward with the supporting leg and to bring the center of the mass over the stair. In this case both the distance taken from the stair as well as the height of the stair are critical.

This simple analysis of the motion suggests that both the distance from the initial position of the feet to the stair as well as the height of the stair represent together two relevant variables for climbing the stairs. Our hypothesis was that the geometrical slope (l) defined by the side of the stair riser height (h_s) and the side defined by the distance (d) taken from the lower edge of the stair to the initial position of the feet before the initiation of the movement, could be a good linear approximation for the slope described by the trajectory of the center of mass (see Fig. 1). The question is whether participants were using the slope as a perceptual parameter for their performance. Notice in Fig. 1 the angle α , which represents the trigonometric resultant of the ratio between the riser height of the stair and the hypotenuse of the right triangle. Our hypothesis was that participants, while choosing different distances (d) and different riser height (h_s), would maintain constant the proportions between these variables and, as a consequence, all of them would chose the same angle α . If this is the case, the angle α would correspond to the perceptual information for stair climbing “picked up” by all the participants despite their different age, body size and skill level.

We tested our hypothesis by linearly regressing the value of the hypotenuses (l) as a function of the riser height of the stairs climbed (h_s) individually for all the participants and calculated the coefficient of determination of the fitting line.

Fig. 2 shows data for all participants with the coefficient of determination of the linear regression. This was very high ($R^2 = 0.97$), showing the strength of the relationship. Notice that the young adults are clustered at the top while the older adults and the children are at the bottom of the figure. The high coefficient of determination demonstrates the strength of the relationship determined by the slope which

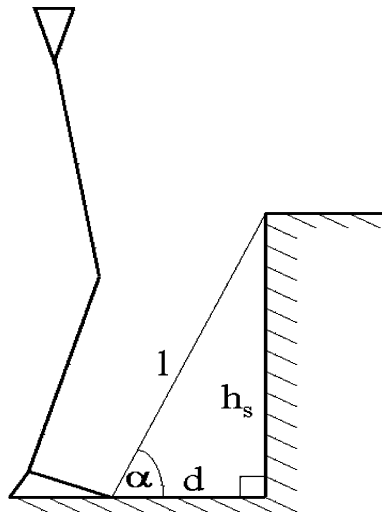


Fig. 1. A model of stair climbing where (d) is the distance taken from the tip of the foot to the bottom of the stair, (h_s) is the height of the stair and (l) is the hypotenuse and α is the angle included. The hypotenuse is defined as the distance from the tip of the foot to the top edge of the stair.

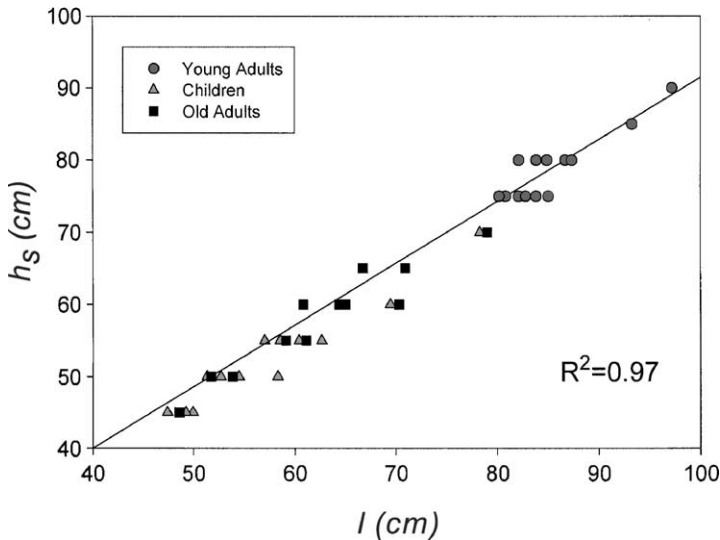


Fig. 2. Linear regression and coefficient of determination between the hypotenuse (l) and the height of the stair (h_s) climbed, for children (Δ), young adults (\circ) and old adults (\blacksquare).

corresponds to the α angle defined in Fig. 1. The measure of the angle was in the mean 68.3° ($SD = 5.2$), which means that the height of the stair chosen (h_s) was for all participants 2.5 times higher than the distance (d) taken. Indeed this angle was the same for all participants thereby showing it is a good candidate for the perceptual body scaled parameter used by all of them despite their difference in age, anthropometrics measures and skill ability.

In order to test the angle α when the stairs chosen by participants were not the highest one, we then considered the data from the lower stairs climbed by all participants and specifically the stairs ascended that were 5 cm, and 10 cm lower than the maximum one climbed. This time we performed the same regression between the hypotenuse (l) and height of the stair (h_s) but considered the three groups separately.

Fig. 3 shows three plots of data with the hypotenuse (l) as a function of (h_s) for old adults (at the top), for children (in the middle) and for young adults (at the bottom). Each plot presents three linear fitting lines for the highest stair, the one 5 cm lower, and the one 10 cm lower. As shown in the plot related to the young adults data, the three slopes decrease systematically from the highest stair climbed, to the stair lowered by 5 cm and the stair lowered by 10 cm. Children, as shown in the middle plot, present the same slope for the highest and the stair lowered by 5 cm, while the slope decreases for the stair lowered by 10 cm. For old adults, on the contrary, the three slopes remain practically the same for the three stair heights. In addition, for children and for young adults the coefficient of determinations of the linear regressions decrease from the 5 cm to the 10 cm lower stairs, while for old adults the coefficient of determinations remain similarly high for both the 5 and the 10

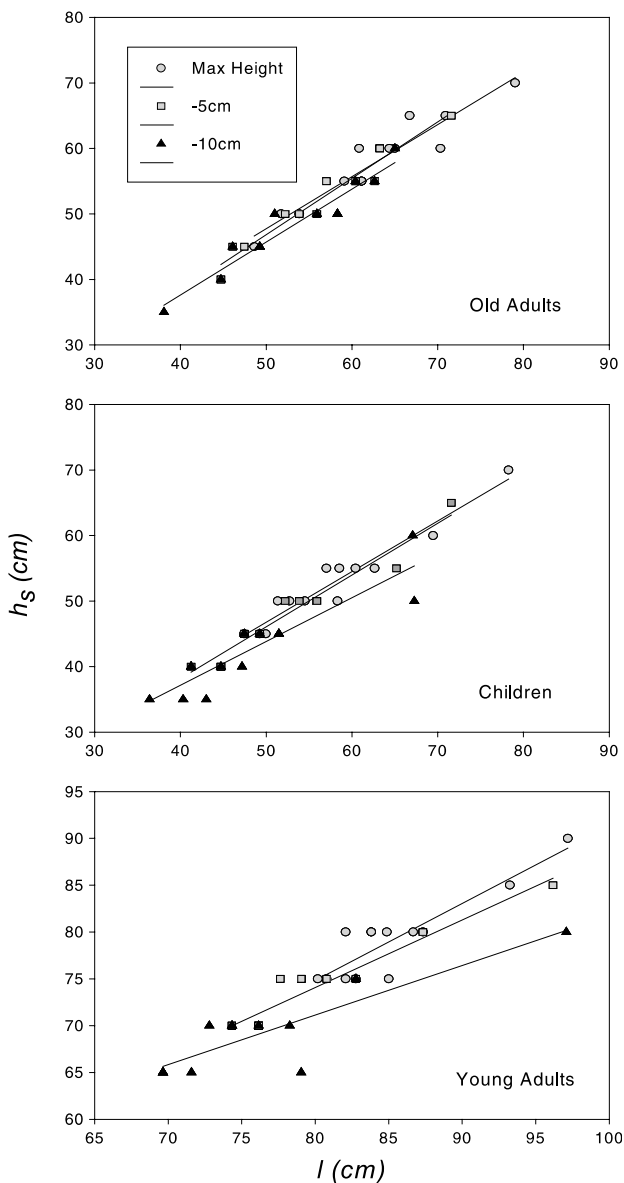


Fig. 3. Three plots showing the linear regression between the hypotenuse (l) and the height of the stairs climbed that were five (\square) and ten (Δ) centimetres less than the highest one (\circ). The graph at the top shows data for old adults, the graph in the middle for children and the graph at the bottom for young adults.

cm lower stairs. In particular, children drop the coefficient from 93% to 83%, young adults from 90% to 76%, while old adults maintain the coefficient stable between 91% and 94%.

6. Kinematics data for young and old adults

For the kinematics data, the 13 participants of the young adults group and the 13 participants of the old adults group were compared. We did not collect kinematics data for children since the task was particularly difficult for the collection of clean data in particular for the youngest one. The trials under analysis were the ones performed at the highest stairs climbed. The t -test for the total movement time between the two groups was not significant, $t(24) = 0.11$, as well as the instants of time at the maximum knee joint closure of the stepping leg, $t(24) = 1.33$. The total movement time was in the mean 2.7 (s) for both groups and the mean time for the maximum closure of the knee angle was 1.7 (s). We then compared the trajectories defined on the sagittal plane for the marker positioned at the ankle joint of the stepping leg. For each participant we calculated the mean among the three trials and we considered:

- the range of the horizontal displacement h_d ;
- the range of the vertical displacement v_d ;
- the slope (v_d/h_d) to derive the angle α_a described by the marker at the ankle.

There was a difference for the horizontal range h_d as well as for the vertical range v_d between the two groups; $t(24) = -2.19$ for the horizontal and ($t = -10.5$ for the vertical range), but no statistical difference for the slope (v_d/h_d), $t(24) = -1.3$ meaning that both groups maintained constant the angle between the ankle trajectory on the sagittal plane and the floor. For young adults the mean angle was 54° and for old adults 52° , the 2° difference between the young and the old adults was given by the fact that older adults were stepping more forward on the stair as compared to young adults, but the difference between the two groups was not significant.

Since one of the hypotheses for having different movement strategies among children, young and old adults was their different joint flexibility, we compared between the two adult groups, the maximum hip angle closure reached during the motion, and we compared among the three groups (the children, the young and the old adults), the maximum hip angle closure attained during the flexibility test.

Fig. 4, shows for the graph on the right side the maximum closure of the hip angle attained during the flexibility test for children, young and old adults, and the maximum closure of the hip angle attained during the motion for the young and the old adults. As presented in the graph, children and young adults show greater flexibility compared to old adults, the result was confirmed by the ANOVA that was significant $F(2, 36) = 48.31$ and by the Tukey's test. Moreover, young adults present a significantly higher flexibility during the motion when compared with old adult, $t(24) = 2.18$. The graph of the left side of the figure shows the relationship between the height of the maximum stair climbed by each participant as a function of the maximum hip angle closure during the flexibility test. As shown in the graph for the two adult groups the highest stairs climbed are correlated with the hip flexibility measures. On the contrary, children show the same hip flexibility measures as young adults do, but at a lower stairs height due to their difference in body size.

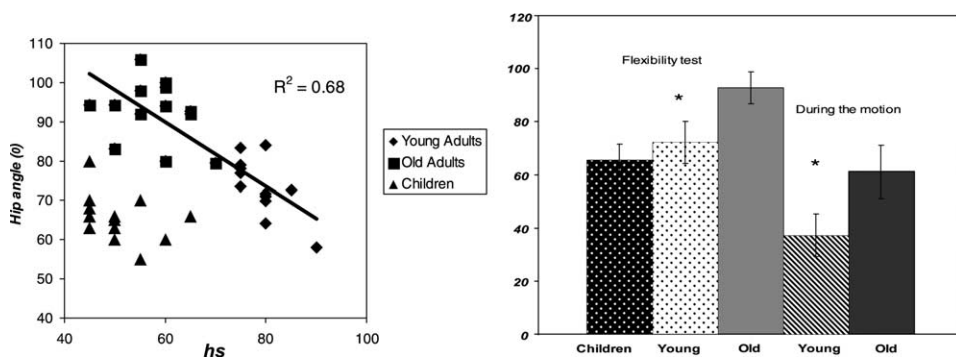


Fig. 4. Two plots: on the right of the figure the comparison between children, young and old adults for the values of the maximum hip angle closure for the flexibility test, and the comparison between young and old adults for the value of the maximum hip angle closure attained during the climbing of the highest stair. The star symbol states the significance at $p < 0.05$. On the left of the Figure a linear regression with the coefficient of determination for the values of the maximum hip angle closure for the flexibility test and the value of the highest stair climbed for young and old adults. Children data are presented as well.

7. Discussion and conclusion

The main result of this study is the definition of a new perception–action model for stair climbing. We found that the ratio between the distance from the participant's feet to the top edge of the stair (l) and the height of the stair (h_s), was similar for children, young and old adults to accomplish the task. The angle α included within the two sides (l) and (d) (see Fig. 1) was indeed the same for all participants despite differences in body size, age and joint flexibility following the similarity hypothesis (McMahon & Bonner, 1983; Pufall & Dunbar, 1992).

We showed that from 5 to 21 years of age, the selection of the highest stair was similarly scaled based on leg length. In contrast, we showed that for old adults, from 53 to 72 years of age, the leg-length scaling factor was significantly different. Concerning the stairs actually climbed, we found a statistical difference between the three groups. Young adults were able to climb stairs as high as their leg length while children were able to climb stairs that were high 88% of their leg length. We speculate that the extremely dexterous physical fitness of the young adults was affecting the performance as Meeuwse (1991) already demonstrated. Indeed we should mention that the young adults recruited in this study were all students from the Movement Science and Sport Department. As far as old adults are concerned, they were climbing stairs that were significantly lower than young adults even though they were of the same body size. By considering all these previous results together, we showed that the simple scaling factor based on the leg-length it is not an appropriate ratio for stair climbing.

The ability to express joint flexibility, particularly during the first phase of the task (the stepping), constrained the participant to select both a suitable stair height as well as a distance from their feet to the stair before the initiation of the movement.

In particular, the distance taken from the stair is critical to allow the stepping foot to reach the top without hitting the stair and, given a certain stair height, the closer the initial body position is to the stair, the more flexibility is required. Because of this, here we propose that instead of the body-scaled ratio height of the stair:leg-length, the geometric angle α (see Fig. 1) is the invariant that can be perceptually used and is common over a wide range of ages despite the different anthropometrics measures and skill level.

The common angle corresponds to a defined proportion between the two variables “picked up” by the climbers: the height of the stair (h_s) and the distance from the stair (d) such that h_s is 2.5 times bigger than d . Since potentially the angle α can be visually detected before the initiation of the movement, we propose that it could represent the relevant information used by participants to guide their action.

The angle α can be thought of as a parameter that assures a successful motor solution due to the existence of constraints (Newell, 1991) that guide the climber in identifying the limits on action for then selecting the most efficient path for the action. Moreover, when the data from the lower stairs were considered, old adults, contrary to children and young adults, maintained the same angle α for all the stairs climbed, including the ones that were 5 and 10 cm lower than the highest one. This result shows that old people applied the same constraints even for easier tasks, namely keeping stable the proportionality between the stair height and the distance taken from the stair. On the contrary, young adults and children, felt progressively less constrained by the lower stairs and more able to climb them by selecting dissimilar distances (d) namely, in choosing either a smaller or a bigger distance from the stair before the initiation of the movement.

Since the actions emerges from the continuous coalition and adjustments between body and environmental constraints (Newell, 1991), we speculate that by varying the task let's say by changing the stair shape or the width of the tread, the angle measured will differ from the one found in this experiment but it will remain invariant within the same task.

The kinematics of the ankle trajectory supported the geometric results. We found that the horizontal and the vertical displacement of the ankle trajectory on the sagittal plane differed between young and old adults, while the ratio between the two remained constant. The angle α_a between the ankle trajectory and the line of the floor was indeed the same for all the participants.

The total movement time, as well as the moment of maximum closure of the knee joint, did not differ between the two groups. Both groups performed the self-paced motion within the same range of time, even though different stairs were chosen. Climbing stairs implies the losing and the regaining of total body balance, respectively during the stepping phase and the pushing phase. Interestingly, the two phases were solved within the same range of time suggesting that for this task movement time was acting as an additional constraint.

One of the explanations for having differences in stair climbing between young and old adults has been related to their dissimilarity in joint flexibility (Konczak et al., 1992). In order to test this hypothesis we compared the minimum angle closure of the hip joint for each participant. Old adults presented a greater hip joint angle

exhibiting consistently less flexibility when compared to young adults and children. As revealed in Fig. 4, hip flexibility and height of the stair climbed are related for young and old adults, indeed young adults climbed higher stairs and presented a more pronounced hip flexibility than old adults. On the contrary, children showed to be as flexible as young adults while they were climbing stairs as height as older adults did due to their smaller body size. In addition, the greater flexibility presented by young adults was particularly pronounced during the motion. Considering the flexibility results combined with the movement time results we suggest that for testing climbing capability, dynamic balance needs to be taken into account.

In conclusion, in order to climb stairs, participants picked up direct relevant information by choosing, before the initiation of the movement, a fixed amplitude of the angle between two sides defined as the distance taken from the feet to the bottom edge of the stair and the distance from the feet to the top edge of the stair. This angle is the perception–action invariance that defines the performance for this task despite different anthropometrics and skill ability. Children as young as 5 years of age are already picking up the same invariance. We speculate that this parameter represents the coalition of constraints necessary to accomplish the task.

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