Exp Brain Res (2008) 186:343–348
DOI 10.1007/s00221-008-1320-1

RESEARCH NOTE

# Visual control of action in step descent

**Dorothy Cowie · Oliver Braddick · Janette Atkinson**

Received: 12 June 2007 / Accepted: 12 February 2008 / Published online: 23 February 2008

**Abstract** Visual guidance of forwards, sideways, and upwards stepping has been investigated, but there is little knowledge about the visuomotor processes underlying stepping down actions. In this study we investigated the visual control of a single vertical step. We measured which aspects of the stepping down movement scaled with visual information about step height, and how this visual control varied with binocular versus monocular vision. Subjects stepped down a single step of variable and unpredictable height. Several kinematic measures were extracted including a new measure, "kneedrop". This describes a transition in the movement of the lower leg, which occurs at a point proportional to step height. In a within-subjects design, measurements were made with either full vision, monocular vision, or no vision. Subjects scaled kneedrop relative to step height with vision, but this scaling was significantly impaired in monocular and no vision conditions. The study establishes a kinematic marker of visually controlled scaling in single-step locomotion which will allow further study of the visuomotor control processes involved in stepping down.

**Keywords** Human · Visuomotor · Locomotion · Stair · Monocular

## Introduction

Everyday locomotion often involves obstacles or significant changes in the physical environment, which must be visually registered and accommodated into the walking pattern. This kind of visual guidance has been examined in anterior–posterior and medio-lateral directions (Lyon and Day 1997), as well as stepping upwards over an obstacle (Patla et al. 1991). However, much less is known about the control of stepping down. Steps down are encountered frequently in both manmade and natural environments and are of applied importance as one of the most frequent causes of falls during walking (Startzell et al. 2000). This paper examines the visually driven adjustments to locomotion made in response to a single step down. We will concentrate on locomotion down a regular step with distinct "platforms" and "risers", though we presume that similar principles apply to less regular surface features that require a descending foot placement in a natural environment.

What is the role of vision in step descent? Beyond the binary decision to attempt a step or not (Warren 1984), visual information about step height enables aspects of movement to be scaled appropriately for the depth of the step. In a series of EMG studies (see Santello 2005 for a review) participants stepped, or made controlled falls, down a step whose riser height varied between trials. These studies show that there is a burst of calf muscle activity just before landing on a step. This activity may increase joint stiffness for landing; crucially, the activity occurs later for deep steps. This ability to scale the onset of the EMG burst to the step height is likely to depend on visual input about

D. Cowie (✉)
Sobell Department, Institute of Neurology,
University College London, 8-11 Queen Square,
London WC1N 3BG, UK
e-mail: d.cowie@ion.ucl.ac.uk

O. Braddick
Department of Experimental Psychology,
Oxford University, South Parks Road,
Oxford OX1 3UD, UK

J. Atkinson
Department of Psychology, University College London,
26 Bedford Way, London WC1E 6BT, UK

the riser height. Craik et al. (1982) found that pre-landing EMG activity disappeared when participants were blindfolded, and was reduced when the surround of the step moved down while the participant stepped. However, this method is not very robust for quantifying how movement depends on vision condition, since defining the burst onset is difficult when it is weak.

An alternative approach to quantifying how movement changes with riser height is to measure kinematics during step descent. The biomechanics of staircase descent have been well characterised in some respects (McFadyen and Winter 1988; Protopapadaki et al. 2007). Furthermore, Riener et al. (2002) showed that during stair descent maximum hip and knee flexion angles depended on stair inclination. However, it was unclear whether the dependence was on tread depth or riser height. Several studies have divided the step down into phases. “Foot placement” (FP), the last phase before foot contact, is associated with extension at lower limb joints, which prepares the body for weight acceptance (McFadyen and Winter 1988; Zachazewski et al. 1993). MacFadyen and Winter simply define FP as beginning halfway through the swing phase and ending on foot contact (MacFadyen personal communication, 2006). We tried to define phases more stringently and determine if the transition between them depended on riser height.

One potential source of visual information to step depth is binocular information. It has been claimed that this provides a cue to depth in locomotor tasks. For example participants increase toe clearance over an obstacle when stepping over it with monocular viewing (Patla et al. 2002). Likewise in an obstacle avoidance task (Chajka et al. 2007) monocular viewing causes participants to make longer fixations on obstacles and the floor, and to increase total movement time. These authors interpret their findings as showing a role of binocular vision in the guidance of locomotion. However, the role of binocular information in stepping down has not yet been studied. It may be important for perceiving the step’s depth, which allows appropriate movement scaling.

This study examined stepping down a single step. In many EMG and kinematic studies participants had prior experience of descending each step, so non-visual information about riser height was available to them. This makes it difficult to infer whether movement scaling to riser height was really visually controlled and predictive.

We carefully determined that control is visual by varying riser height between trials rather than in blocks (so vision must be used on every trial) and by measuring movement in a blindfold condition. We present a novel kinematic marker of visual control which captures how movements are planned on the basis of visual information about step height; and, by removing binocular information, we assess the potential contributions of binocular visual cues to the scaling process.

## Method

### Participants

Ten adults with normal or corrected normal vision took part (mean age 22.1, SD 3.6 years, mean height 173.5 cm, SD 9.8 cm, 5 males). All had normal stereo acuity on the TNO test (Institute for Perception TNO 1972). Eye dominance was measured by asking participants to look through a tube with one eye three times; all participants chose to look with same eye for all three trials and this was taken to be their “dominant” eye.

### Equipment

Kinematic data were recorded using a 6-camera motion tracking system (SMART, Milan) operating at 60 Hz. Cameras fixed at ceiling height surrounded a 13 $m^3$ testing area, allowing accurate 3-D reconstruction of marker positions. On each leg the participant wore a marker on the lateral epicondyl (LE), lateral malleolus (LM), heel (H), and fifth metatarsal head (MH). Participants were barefoot and wore shorts to allow easy camera viewing of the kinematic markers. A simple “step” from an “upper platform” to a “lower platform” was constructed. The height of the upper platform was constant for all trials and step height was varied by changing the lower platform between trials, so the step up at the start of each trial was no guide to the height to be descended.

### Procedure

The task was to take a single step down from the upper platform to the lower platform. The participant took one practice step down to familiarise them with the basic task before markers were attached. Before each trial the participant waited away from the step, which they could not see. On “no vision” trials they were then fitted with a blindfold; on monocular trials they were fitted with an eye patch. On all trials they then closed their eyes and were led to the upper platform. On vision and monocular trials they were instructed “open your eyes and step down when you are ready”; on no vision trials they were instructed “step down when you are ready”. They were asked to step off the upper platform onto the lower platform as normally as possible, leading with one foot.

### Step dimensions

Riser heights were scaled to leg length to allow comparison between participants of different height. Leg length was measured as the distance from ASIS to medial malleolus. The height of the upper platform was 24% leg length + 18 mm.

The range of riser heights (8–24% leg length) was designed to be as extreme as was compatible with safety and normal stepping behaviour. For an adult of average leg length (90 cm) shallow, medium, and deep steps were ~7, 14 and 21 cm.

### Design

Within-subjects factors were riser-height (8, 16, 24% leg length) and vision-condition (vision (V), monocular (M), no vision (NV)). Each participant completed 3 blocks, totalling 27 trials. Trial types were randomised within a block, with each block containing all nine riser-height (3) × vision-condition (3) trial types. Half the group (3 males, 2 females) always had their dominant eye covered, half their non-dominant eye (2 males, 3 females).

### Data analysis

Data were analysed using SMART software (BTS, Milan). We extracted several measures from each trial. After analysis, we averaged data from the 3 trials at each combination of riser height and vision condition for an individual participant. Since the purpose of this study was to discover how movement is scaled to a vertical environmental feature (the step), we developed a new measure, "kneedrop", to capture the movements of the leg relative to the vertical.

To measure kneedrop (Fig. 1a) we first defined the lower leg segment between the knee (LE marker) and ankle (LM marker), and measured the saggital plane angle ("swing") between this segment and the vertical over the course of the stepping movement (Fig. 1a). Changes in this angle reflect not only flexion at the knee but also the orientation of the body relative to vertical. For all participants, swing showed the same characteristic pattern during descent—the leg swings outwards to a peak then swings inwards again. We defined swing peak as the point at which the rate of change in swing angle approached zero (was 1.5° or less). We then calculated the vertical position of the knee (LE marker) as the body descended the step. "Kneedrop" was defined as the knee's vertical descent from its maximum height to the

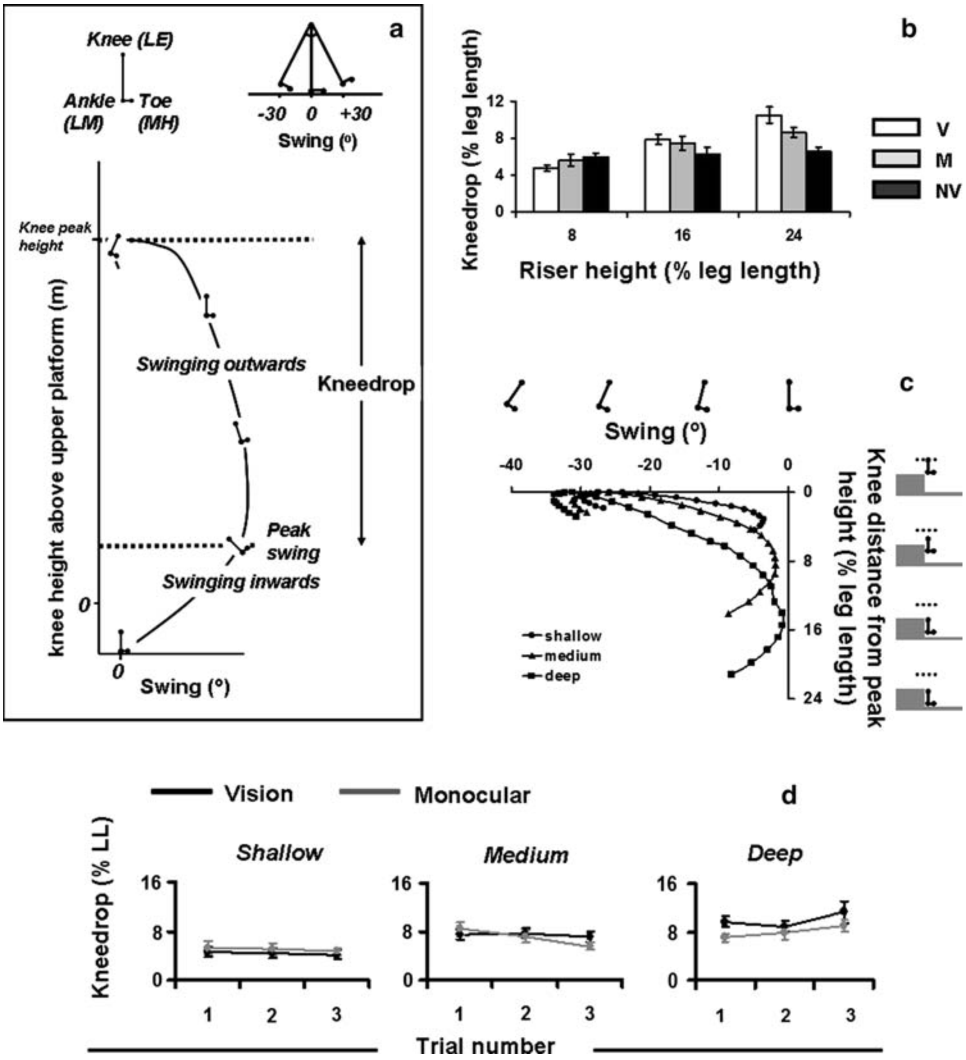

**Fig. 1** **a** "Swing" is the angle between the calf segment and the vertical. Kneedrop is the distance that the knee descends from its peak while the leg swings outwards. **b** Mean and standard errors of kneedrop in vision (*V*), monocular (*M*) and no vision (*NV*) conditions. **c** Example trials from one participant. As the leg swings towards vertical (*x* axis), the knee drops (*y* axis). When the leg is closest to vertical, the knee has dropped further for deep steps than shallow. **d** Learning across trials in V and M conditions

swing peak. In other words it measures how far the knee has dropped vertically from its peak, at the time when the leg has ceased to swing outwards and is beginning to swing back.

We hypothesised that the location of the swing peak might change with riser height but that this would depend on the visual information available. To test this we conducted a repeated measures ANOVA on kneedrop with factors riser height (shallow, medium, deep) and vision condition (V, NV, M). Significant results were followed up with further ANOVAs to determine the source of the difference; finally a repeated measures ANOVA on V trials with factor riser height confirmed scaling in the vision condition. We excluded from the dataset any trials which failed to show a swing peak. Since any change in the kneedrop measure might result from a change in knee peak height, we also measured the correlation between each participant's knee peak height and kneedrop on V trials.

We next examined the possibility of learning during the experiment, using a repeated measures analysis at each level of riser height, with factors trial number (1, 2, 3) and vision condition (V, M). As an index of overall movement efficiency we analysed movement duration in a repeated measures riser height by vision condition (V, M) ANOVA. We defined movement onset when the heel was raised 5 mm above the upper platform and movement end when the toe was 5 mm above the lower platform. If monocular viewing caused systematic misjudgements of riser height, one might expect a greater incidence of high-impact, high-velocity landings on the lower platform in the M condition than in the V condition. To test whether this was the case we conducted a repeated measures riser height by vision condition (V, M) ANOVA on landing speed (MH marker resultant speed in three dimensions at movement end).

We expected any effects of riser height to be monotonic, so in all ANOVAs we report linear contrasts for height effects unless otherwise stated. For the same reason we report linear contrasts for effects of trial number. Main effects are reported for all other factors and interactions.

## Results

### Kneedrop

A total of 14/270 trials were excluded from analysis of kneedrop because swing showed no peak (i.e. kneedrop was not measurable). Figure 1b shows mean kneedrop data from the remaining trials, across all participants, riser heights and vision conditions. Figure 1c shows "swing" angle unfolding over space in the vision condition, for a sample trial at each riser height. Peak swing occurs further down the step for deep than shallow steps (kneedrop is larger).

An ANOVA including all riser heights and vision conditions showed a vision-condition by riser-height interaction [$F(4,36) = 12.0$, $p < 0.001$] as well as effects of vision-condition [$F(2,18) = 3.9$, $p < 0.04$] and riser-height [$F(1,9) = 81.9$, $p < 0.001$]. Similarly an ANOVA including riser-height and vision conditions V, NV showed a vision-condition by riser height interaction [$F(2,18) = 27.7$, $p < 0.001$] and effects of vision-condition [$F(1,9) = 7.6$, $p < 0.03$] and riser height [$F(1,9) = 64.4$, $p < 0.001$]. An ANOVA including riser-height and vision conditions V, M showed a vision-condition by riser-height interaction [$F(2,18) = 4.2$, $p < 0.04$], an effect of riser-height [$F(1,9) = 138.7$, $p < 0.001$], but no effect of vision condition [$F(1,9) = 1.2$, $p > 0.3$]. An ANOVA with factor riser-height on V trials showed an effect of riser-height [$F(1,9) = 82.9$, $p < 0.001$]. Taken together, these results show that in the vision condition participants scale their kneedrop to riser height. This scaling is significantly reduced either with no vision or with monocular viewing. Nine participants showed no significant correlation between knee peak height and kneedrop and one participant showed a negative correlation, so increases in knee peak height could not account for the increases in kneedrop we found.

Learning (Fig. 1d) was assessed at each value of riser height. For shallow trials, there was no effect of vision condition (V, M) on kneedrop [$F(1,5) = 1.2$, $p > 0.3$], an effect of trial number [$F(1,5) = 11.5$, $p < 0.02$], with kneedrop reducing as the experiment progressed, and no interaction [$F(2,10) = 0.3$, $p > 0.7$]. Only three participants were included in this analysis, since the other four had at least one trial on which swing did not peak. For trials with medium step height, there was no effect of vision [$F(1,9) = 0.3$, $p > 0.5$], an effect of trial number [$F(1,9) = 5.2$, $p < 0.05$], with kneedrop reducing as the experiment progressed, and no vision condition by trial number interaction [$F(2,18) = 1.9$, $p > 0.1$]. For trials with the maximum step height, there was an effect of vision condition [$F(1,9) = 6.4$, $p < 0.04$], no effect of trial number [$F(1,9) = 1.6$, $p > 0.2$] and no vision condition by trial number interaction [$F(2,18) = 0.7$, $p > 0.5$].

### Secondary measures

An ANOVA on total movement duration (Table 1), showed a significant increase with riser height [$F(1,9) = 54.4$, $p < 0.001$], no effect of vision condition (V, M) [$F(1,9) = 2.9$, $p > 0.1$] and no interaction [$F(2,18) = 2.1$, $p > 0.1$].

Mean landing speed (Table 1) increased with riser height in both V and M conditions. A repeated measures ANOVA on V and M trials showed an effect of riser height [$F(1,9) = 35.8$, $p < 0.001$], no effect of vision condition

**Table 1** Mean and standard errors of movement duration and landing speed in V and M conditions

| | Vision (V) trials | | | Monocular (M) trials | | |
|---|---|---|---|---|---|---|
| | Shallow | Medium | Deep | Shallow | Medium | Deep |
| Movement duration (sec) | 0.60 (0.03) | 0.68 (0.03) | 0.74 (0.03) | 0.57 (0.02) | 0.75 (0.06) | 0.85 (0.08) |
| Landing speed (m/sec) | 0.29 (0.03) | 0.33 (0.03) | 0.49 (0.03) | 0.25 (0.02) | 0.31 (0.02) | 0.48 (0.03) |

[$F(1,9) = 3.9$, $p > 0.08$], and no interaction [$F(1.25,18) = 0.1$, $p > 0.9$, Greenhouse–Geisser corrected] on landing speed. Thus landing speed is not larger on M trials than V trials as one might expect if participants were more often making misjudgements on M trials.

## Discussion

We developed a new paradigm to examine the visual control of stepping down a single step. Visual control of the leg's movement during step descent can be captured by the kinematic measure "kneedrop", the distance dropped by the knee from its peak height to the point where the calf segment reaches its maximum outwards "swing". This parameter must be under visual control since (1) its value scales to the riser height of the step, which in our paradigm must be gained using visual information since participants have no non-visual cues to it; (2) scaling does not occur when participants are blindfolded. Scaling is impaired under monocular viewing conditions.

This scaling process makes the stepping-down movement an efficient one by combining horizontal and vertical translation in stepping down. Like forward stepping (Lyon and Day 1997), it seems that stepping down may be achieved as a controlled fall when the appropriate visual information is present. Kneedrop is not the only measure of visual control in step descent. For example future studies should investigate the relation of the swing peak to prelanding EMG activity (e.g. Santello 2005). However, unlike these EMG measures, kneedrop can be reliably extracted in degraded visual conditions, which will allow future experiments to investigate the sources of visual information important for controlling descent.

While one might have expected monocular viewing to have some general effect on the duration of the step, this was not affected. In contrast covering one eye impaired scaling of kneedrop to step height. One interpretation of this is that binocular information is used to perceive the depth of the step and scale movements to riser height. Thus removing binocular information should cause misperceptions of target distance, which could be responsible for the reduction in scaling we found. An alternative possibility is that with monocular viewing, participants correctly perceive the depth of the step, but add some margin for error in their movement parameters because visual uncertainty caused by reduced field of view leads to cautious movement planning. This kind of effect has been shown in reaching studies (Loftus et al. 2004). In the present study informal observations and comments made by participants suggested that some depth misperceptions occurred. If depth misjudgments occurred in such a task, future studies could use synoptic viewing (Koenderink et al. 1994) to selectively remove binocular disparity, or prisms to selectively manipulate vergence information, showing which binocular cues were most important for these distance estimates. However, our current results are most consistent with a "safety strategy" account. Little learning occurred, and when it did it tended towards caution as the experiment progressed. Likewise landing speeds were not high as "undershooting" the target step would predict. The specific safety strategy used by our participants was to tend towards the mean value of the step depths encountered (or the riser height of an average step, since this was approximated by our medium step). This kind of "contraction bias" strategy has also been reported in open-loop reaching movements (Tresilian et al. 1999).

Our findings are consistent with the results of the few other studies on monocular walking, which report interruptions to locomotor variables with monocular viewing conditions (Patla et al. 2002; Chajka et al. 2007). In these studies it may also be the case that monocular viewing caused participants to add a safety margin onto their estimates because of a reduced field of view. Indeed Patla et al. found that participants walking monocularly over an obstacle increased toe clearance over the obstacle, which represents a safety margin during obstacle crossing.

In summary, our novel kinematic measure provides a useful tool for assessing the sensitivity of stepping actions to environmental parameters during stair descent, analogous to measures developed for analysing single steps forward, medially or upward over an obstacle. In particular it shows that stepping actions are regulated by visual information about riser height, and demonstrates the kind of response that participants make when visual information is degraded or removed during a step down.

**Acknowledgments** This work was supported by an MRC studentship to DC, and the Williams Syndrome Foundation UK.

## References

Chajka K, Vecellio E, Hayhoe M, Gillam B (2007) The role of binocular vision in navigating obstacles. J Vis 7:119a

Craik RL, Cozzens BA, Freedman W (1982) The role of sensory conflict on stair descent performance in humans. Exp Brain Res 45:399–409

Institute for Perception TNO (1972) TNO test for stereoscopic vision. Laméris, Utrecht

Koenderink JJ, van Doorn AJ, Kappers AM (1994) On so-called paradoxical monocular stereoscopy. Perception 23:583–594

Loftus A, Murphy S, McKenna I, Mon-Williams M (2004) Reduced fields of view are neither necessary nor sufficient for distance underestimation but reduce precision and may cause calibration problems. Exp Brain Res 158:328–335

Lyon IN, Day BL (1997) Control of frontal plane body motion in human stepping. Exp Brain Res 115:345–356

McFadyen BJ, Winter DA (1988) An integrated biomechanical analysis of normal stair ascent and descent. J Biomech 21:733–744

Patla AE, Niechwiej E, Racco V, Goodale MA (2002) Understanding the contribution of binocular vision to the control of adaptive locomotion. Exp Brain Res 142:551–561

Patla AE, Prentice SD, Robinson C, Neufeld J (1991) Visual control of locomotion: strategies for changing direction and for going over obstacles. J Exp Psychol Hum Percept Perform 17:603–634

Protopapadaki A, Drechsler WI, Cramp MC, Coutts FJ, Scott OM (2007) Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. Clin Biomech 22:203–210

Riener R, Rabuffetti M, Frigo C (2002) Stair ascent and descent at different inclinations. Gait Posture 15:32–44

Santello M (2005) Review of motor control mechanisms underlying impact absorption from falls. Gait Posture 21:85–94

Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR (2000) Stair negotiation in older people: a review. J Am Geriatr Soc 48:567–580

Tresilian JR, Mon-Williams M, Kelly BM (1999) Increasing confidence in vergence as a cue to distance. Proc Biol Sci 266:39–44

Warren WH Jr (1984) Perceiving affordances: visual guidance of stair climbing. J Exp Psychol Hum Percept Perform 10:683–703

Zachazewski JE, Riley PO, Krebs DE (1993) Biomechanical analysis of body mass transfer during stair ascent and descent of healthy subjects. J Rehabil Res Dev 30:412–422