DO INFANTS HAVE MOTOR RESPONSES TO SUDDEN SURFACE ROTATIONS IN PRONE POSITION?

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Abstract — This study investigated whether sudden rotation of the support surface (platform) triggers motor responses similar to reactions to sudden free fall in infants at very early age (2 to 5 weeks). Ten infants in prone position were exposed to sudden head-down rotation (mimicking the falling phase) and head-up rotation of the platform (mimicking landing phase) of 4° or 6° amplitude and 35°/s velocity while EMGs and kinematics were recorded from the neck, trunk, and right arm. One infant, reassessed at 13 weeks, and one adult were tested for complementary developmental information. Sudden downward acceleration of the platform, induced either during head-down rotation or during the deceleration phase of head-up rotation, indeed mimicked falling and evoked in infants two-peaked EMG responses in the neck, trunk, and arm muscles, lasting in the latter over several hundred milliseconds. The activation pattern showed similarities to the adult and 13-week-old control subjects. The results suggested that the first burst may be ascribed to cutaneous pressure changes at the body and to vestibular signals triggering a startle-like response, whereas the second burst of the pattern in the arm is likely a candidate for an early substrate of the landing response normally seen during later stages of motor development. Head control appeared to be related more to its position with respect to the orientation of the trunk rather than to space in the infants and in the adult and might be due to the experimental paradigm, in which the surface accelerated away from the body and not, as during normal falling, when the body accelerates toward the support surface.

Introduction

Falling is a powerful stimulus to the postural control system. Studies of reactions to falling have been performed mostly in young normal adults, probably because the apparatus for suspending the subject and the procedures used for suddenly releasing the subject in free fall were not considered safe enough for the investigation of children or disabled people.

In adult humans, landing on the feet from an unexpected fall is preceded by accurately timed activity in the calf muscles prior to landing (1,2). It is common knowledge that in children a fall during independent walking evokes a defensive reaction, protecting the body from injury. The protective reaction, known as the landing response, is aimed to protect the head from colliding with the ground and develops in children between the 6th and the 9th month (3). The landing response includes two successive phases: 1) the free falling phase, during which different sensory inputs associated with a fast downward movement of the upper part of the body evoke a specific motor pattern, preparing the child for contact with the ground; and 2) the ground contact, in which a specific body configuration—upward arching of head and trunk and protraction of the arms as well as additional activation of muscle groups (evoked by the contact with the ground)—results in a "safe landing."

In the developmental literature, the behavioral expression of upward arching of the trunk and head in the prone position is known as the Landau reaction, a reactive postural response to
horizontal suspension (4). The earliest part of the response is present at 2 months of age. Sudden forward and downward tilt of infants from vertical suspension is known as the “parachute reaction” (5,6), a reactive postural response triggered from visuovestibular signals, occurring in children at about 9 months of age. Response characteristics are protraction and slight abduction of the arms and support on the hands with extended and spread fingers. Sudden tilts to lateral from a sitting position are known as protective reactions to lateral, having a pattern in the arms and hands similar to the parachute reaction and occurring at about the same stage in development (7,8).

Greenwood and Hopkins (9) have shown in adults that in the control of landing on the feet from unexpected falls, the muscular response in the soleus has two peaks. The onset of the first peak was related to the fall, and the second peak was related to the landing, accurately timed to occur prior to the moment of landing. The first peak is described by Melville Jones and Watt (1) as a preprogrammed muscle response originating in the otolith apparatus, whereas Greenwood and Hopkins (9) listed the first peak as analogous to a startle response, probably originating in the otolith apparatus. They listed the second peak as related to landing, accurately timed to occur prior to landing.

By using a “safe” experimental design in which the support surface accelerates away from the body and thereby imitates the onset of a fall, I investigated in this study whether some components of the reaction to falling and of landing on the hands are present in very young infants (2 to 5 weeks old), long before the protective landing response (parachute reaction) can be elicited. The infant was positioned prone on a movable platform in front of the rotation axis of the platform. The platform movement was considered to simulate falls by sudden downward accelerations (head down rotation) and “landings” by sudden upward acceleration (head-up rotation). The experiments were performed in collaboration with M. Hadders-Algra and H. Forssberg at Karolinska Hospital. The collaborators will focus their analysis of the experiments to investigate if automatic postural responses to surface perturbations are present at this age.

**Methods**

Ten healthy infants between 2 and 5 weeks of age participated in this study. In addition, one infant was reassessed at 13 weeks of age, and one adult (age 18 years) was tested during the analysis phase of the study for complementary information. The infant was placed prone on a movable platform. The motor-driven, computer-controlled platform consisted of a hard wooden plate (600 × 1200 × 13 mm) which could rotate about an axis running across the width of the plate, parallel to and level with the surface. The wooden plate could thus be rotated in the infant’s sagittal plane. The infants were undressed and positioned in prone in front of the rotation axis of the platform with the head turned to the right side of the body (Figure 1). One parent and one experimenter sat close to the platform ready to take up the infant if there was any discomfort. Platform movements were elicited only when the infant was lying prone without movements of the head or arms. The platform movements consisted of 10 head-down and 10 head-up rotations with 4° amplitude and 35°/s speed. Three of the infants were additionally exposed to head-up and head-down rotations of 6° at 35°/s. For both amplitudes, the velocity of platform movement was reached within 50 ms after onset of the perturbation, and the deceleration occurred within 50 ms before the platform movement stopped. The duration of 4° perturbation was 140 ms and of 6°, 180 ms.

**EMG Recordings**

Bipolar surface EMG electrodes with an interelectrode distance of 15 mm and built-in amplification of 2000, (MYO 115, Liberty Technology, Hopkinton, MA, USA) were applied over the belly of the wrist extensor (carpi radialis, EXC), wrist flexor (flexor carpi radialis, FLC), elbow flexor (biceps brachii, BIC), elbow extensor (triceps brachii, TRIC), neck flexor (sternocleidomastoid, NF), neck extensor (at the C4–C5 level, NE), thoracic extensor (at the level T6–8, TE), and lumbar extensor (at the L1–L2 level, LE) on the right side of the body (Figure 1). Either TE or LE recordings were of
unacceptable quality in 5 infants, and as the recording in the other infants indicated that TE and LE were usually activated in concert, the best records of either TE or LE were analyzed. In addition the adult control subject had a surface electrode attached to the orbicularis oculi muscles above the right eye for recording of the eyeblink response. The electrodes were electrically isolated from the rest of the system. The raw signals were band-pass filtered between 10 Hz and 1 kHz.

**Kinematics**

Body and platform movements were synchronously recorded with the EMGs using an ELITE system (BTS, Milan, Italy) with two CDD cameras at a sampling rate of 100 Hz. Eleven reflective markers (diameter 6 mm) were used (Figure 1). Eight markers were attached to the right side of the body at the following positions: 1) 5 cm above ear level; 2) at ear level; 3) process spinous C7; 4) apex of sacrii; 5) posterior superior ili spine (pelvis); 6) acromion (shoulder); 7) epicondyle of the radius (elbow); and 8) process styloides ulnae (wrist). The remaining three markers were mounted on the edge of the platform (9–11). Marker 10 was mounted colinear to the rotation axis of the platform, with marker 9 to the left and marker 11 to the right of marker 10 (Figure 1). The two cameras were placed 1.5 m from the platform, at 45° angles to the sagittal plane. The displacement of all markers was recorded for 3 s, starting 1 s prior to the perturbation. After the experiment, segment angles (that is, angular change of body segments in space) were calculated for the head (by a vector joining markers 2–1) and the pelvis (markers 4–5) in relation to the horizontal axis. The elbow angle was estimated by calculating the angle of the two intersecting vectors between markers 7–6 and 7–8, respectively. Relevant positional and angular data were transformed into ASCII files and sent to SC/ZOOM (a flexible laboratory computer system; Department of Physiology, Umeå University, Sweden) for further analysis.

**Data Acquisition and Analysis**

The signals from the platform and the EMGs were sampled at 400 and 800 Hz, respectively, digitized at 12-bit resolution, and stored on SC/ZOOM for later off-line analysis. The EMG burst onset latencies were measured from the onset of the platform rotation signal on the raw EMG signal for each muscle in order to differentiate from signal artifacts. The onset latency was defined as the time the EMG burst first exceeded the baseline level by +2 SD and was maintained above baseline level for longer than 30 ms. For presenting average figures, the root mean square of the raw signal was computed using a 6-ms moving window to rectify and average the records. These results for 5 trials of head-down platform movement were then averaged. The ki-
nematic data was imported to SC/ZOOM, and a graphics terminal was interactively used to define time events of position trajectories. The computation of the net vertical displacement, subtraction from the time varying amplitude of the vertical displacement of the platform (marker 11) of head (marker 1), elbow (marker 7), and wrist (marker 8) was performed on the ASCII data using the following correcting formulae in which x, y before the marker number indicates the x, y coordinates for the marker: Head/diff. = \( y_1 - (y_{11} - y_{10})/(x_{11} - x_{10}) \times (x_1 - x_{10}) \), elbow/diff. = \( y_7 - (y_{11} - y_{10})/(x_{11} - x_{10}) \times (x_7 - x_{10}) \), wrist/diff. = \( y_8 - (y_{11} - y_{10})/(x_{11} - x_{10}) \times (x_8 - x_{10}) \). The procedure was performed for each sample of the 3-s record.

Statistics are presented for the EMG analysis based on 5 trials of each perturbation mode for

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**Figure 2.** A single trial of raw EMGs and trajectories of segment angles of head, pelvis, joint angle of elbow (Arm), and vertical displacement of wrist, elbow, and head (Y-direction) of one 2-week-old infant during head-down rotation (A) and head-up rotation (B). Note that the amplitude of platform movement is not subtracted from the position traces of the arm and head segments. The platform movement onset is indicated by the vertical line through all traces. The first trace shows the platform rotation recorded as an analog signal together with the EMG, and the last trace shows the vertical displacement of the platform, received from the position trace of marker 11. Recorded muscles: NF, neck flexor; NE, neck extensor; LE, lumbar extensor; BIC, biceps brachii; TRIC, triceps brachii; FLC, wrist flexor; EXC, wrist extensor. Positive going traces indicate a backward rotation for head and pelvis; for the arm, an extension of the elbow angle; and for HEAD/Y and WRIST/Y, a vertical upward displacement.
Infant Posture Control

The Wilcoxon matched pairs test was used to compare onset latencies between muscles and amplitudes of platform perturbations within infants and between conditions. Statistical significance was determined at at least the $P < 0.05$ level.

**Results**

*Movement and EMG Response Patterns*

Both head-down and head-up rotations (Figure 2) elicited distinct EMG bursts in arm and wrist muscles with a duration of several hundred milliseconds. The activity in the neck and trunk muscles was less pronounced. The overall EMG pattern looked similar in both head-down and head-up rotation, whereas the body segments moved with the platform in opposite directions during the two perturbation modes. In all infants, the shape of the EMG implied a two-peak pattern that was more pronounced in the arm than in the neck muscles. To ensure that the small amplitude change in the response of the neck muscles was not due to insufficient electrode placement, the Moro-drop reaction was tested at the end of the experiment by holding the infant in supine position with the head and buttocks supported by the hands of the experimenters. The sudden head drop was recorded with a subminiature ($3.7 \times 4.0 \times 9.0$ mm and 0.4 g) piezoresistive, linear accelerometer (type G 125, Semiconductor Products, Ridgefield, New Jersey) mounted at the temple of the head. The head drop induced massive activity in the neck flexor (NF) and a proximal-to-distal sequence of onset of activity in the arm muscles (Figure 3).

*Temporal Sequencing of Onset Latencies of Movements and EMG*

The head-down rotation of the platform passively induced a vertical displacement of the wrist and a change of the elbow angle within 10 ms after platform movement onset. The vertical displacement of the head was significantly delayed from wrist and arm displacement ($35 \pm 17$ ms, $P < 0.05$). The onset of the passive movement of wrist, arm, and head during head-up rotation did not differ from the onset latencies of head-down rotation ($P > 0.05$). During both head-down and head-up rotation, the pelvis tilted backward (Figure 2), resulting in a more flexed trunk position after the platform movement stopped. The mean onset latency to neck and arm muscles during head-down rotation was between 92 and 101 ms ($\pm 43.47$ ms), with no significant delay between muscles ($P > 0.05$). The NF and NE showed similar onset latencies during head-up rotation, whereas the onset to the arm muscles was significantly later (mean difference $44 \pm 22$ ms, $P < 0.05$, Figure 4).

For information about how the mature nervous system responds to sudden head-down rotation of the platform, we tested one adult using the same paradigm. Figure 5 shows the average of five head-down rotations. The responses started during the platform movement, and that is illustrated by the acceleration trace of the platform signal. In this subject, in addition to the neck and arm muscle EMG, the eyeblink response is shown. Eyeblink response onset was
at 34 ± 7 ms, followed by EXC at 61 ± 11 ms, NE 67 ± 15, NF 76 ± 40, TRIC 83 ± 9, and FLC 85 ± 11.

Further, to gather information about how the response changes during development, one infant was reassessed at 13 weeks of age. The average response (5 trials) to head-down rotation is shown in Figure 5, middle panel. The sequence of activation was FLC 58 ± 19 ms, TRIC 77 ± 24 ms, EXC 97 ± 15, and NF and NE at 104 ± 39 ms and 108 ± 35 ms, respectively. For comparison, the EMG response at 2 weeks of age (average of 5 trials) is shown for the same infant. The EMG has similar shape at 2 weeks and at 13 weeks, except that in the latter, the neck muscles have increased duration. During both assessments, the infant's head was turned to the right, while the adult's head was straight, with the forehead supported on the platform. In order to investigate if EMG onset latencies were correlated with the platform acceleration during head-down rotation and with the platform deceleration during head-up rotation, the amplitude in some trials was changed from 4° to 6° with unchanged velocity (35°/s). The results indicated that during head-up rotation of 6° amplitude, the onset latencies of the arm muscles were significantly later (mean dif-
ference $47 \pm 19$ ms, $P < 0.05$), but not those of the NF ($P > 0.05$, Figure 6).

Differences between the Amplitude of the Platform Movement and the Amplitude of Head and Wrist Movement

After subtracting the platform movement (vertical displacement of the platform during head-down, respectively, head-up rotation) from the vertical displacement of head and wrist over time, it was possible to investigate if a change of contact between body segments and the platform occurred during the perturbation. It is expected that if wrist or head have continuous contact with the platform during and after the platform perturbation, the net traces of the vertical displacement of head or wrist over time fall in a straight line after the subtraction from the platform movement. Figure 7 illustrates the results. After subtraction of the platform movement, head and wrist traces showed a deflection from the platform immediately after the onset of the head-down rotation (for example, acceleration phase of the platform movement). During head-up rotation, the deflection of wrist and head traces was associated with the deceleration phase of the platform movement. In the majority of responses, the head traces after the platform movement stopped did not significantly differ from the initial position traces ($P < 0.05$), indicating that, at this age, infants did not show changes of head position, either following head-down rotation or following head-up rotation. Sometimes the head trace was some millimeters lower following head-down rotation compared to the initial position trace, indicating that the head was turned leftward during the perturbation. The wrist position traces were unchanged after the platform movement stopped, which indicated that the wrist was in contact with the platform and that the arm muscle activity was tailored for the landing phase.

The subtraction procedure for the net head and wrist movement were also performed for the adult and the 13-week-old infant (Figure 8). The platform movement induced at the head a double-peaked mechanical response to the acceleration and deceleration of the platform movement in the adult and in the infant at both age intervals. Also, the wrist was maintained on the platform surface. That the wrist traces are some millimeters below the baseline after the stop of the platform movement suggests a supination of the lower arm. The adult shows an upward movement of the elbow marker, suggesting an extension of the elbow. A tendency to a similar pattern is seen in the elbow trace of the infant at 13 weeks of age. At 2 weeks of age, the same infant showed a tendency to an upward movement of the elbow, although several hundred milliseconds later (Figure 8, right panel).

Discussion

Motor Responses and Displacement

The present study revealed that sudden rotations of the support surface trigger in infants reactions similar to motor responses to sudden free fall (9,10) and were comparable to the adult control response in this study. Sudden downward acceleration of the support surface indeed mimicked falling and induced motor responses in arm and neck muscles during the perturbation that lasted for several hundred milliseconds in infants of 2 to 4 weeks of age. The onset latencies to the
VERTICAL DISPLACEMENT
(after subtraction of platform movement)

![Graphs showing head-down and head-up rotation](image)

**Figure 7.** Upper graph: Two trials of the net vertical displacement are shown in position traces of head and wrist of one infant for head-down and head-up rotation, respectively. The amplitude of the vertical displacement of the platform has been subtracted according to the correcting formula described in Methods. Lower graph: One trace of head displacement (different child) after subtraction of the platform movement is compared to a model of how the head trace should look when arching of the neck is present in the landing response (above the shaded area). That the head trace is below the level of the initial position indicates that the infant rotated the head towards the middle after the passive, mechanical response.

Pattern of the muscle responses in the arm and trunk (TE) were associated with the acceleration phase of the head-down rotation or with the deceleration phase (sensed as downward acceleration) of the head-up rotation. In contrast, the onset latencies of neck muscle activity were associated with the first acceleration phase (downward for head-down rotation and upward for head-up rotation). When the vertical displacement of the platform movement was subtracted from the vertical displacement of head, elbow, and wrist, the immediate deflection of the head, elbow, and wrist traces reflected changes of the support of arm and head on the platform surface and represent the passive mechanical responses to the platform acceleration and deceleration (Figure 7, model). Hence, falling is a powerful stimulus to the postural control system, and the
passive mechanical responses presented here may elicit sufficient stimulus of the vestibular and somatosensory system for signalling a fall. It seemed that head control was aimed at orienting the head with respect to the trunk in the adult subject and in the 13-week-old infant, whereas the 2- to 4-week-old infants had the head supported on the platform. Onset of head-up rotation of the platform was not effective for mimicking the impact on the arms during landing or for inducing an arching of the trunk.

Experimental Paradigm

Because in this experimental setup, for reasons of safety, the surface was accelerating away from the body to mimic a fall, it could be argued that this paradigm is not comparable to functional falling reactions when the body accelerates towards a surface, as other investigators have used (2,9). However, Bisdorff and colleagues (10) have recently used a setup similar to that of the current study. Young and elderly subjects lay supine on a couch that had the rotation axis at the foot end. The couch was released from a 10° tilt and gently braked by heavy rubber bands when returning to horizontal position. The fall duration was about 300 ms. The latency to the onset in the young subjects was for NF 57 ± 10 ms, for abdominal muscle 65 ± 12 ms, for quadriceps 75 ± 14 ms, and for tibialis anterior 80 ± 12 ms. These values are in agreement with the latencies of the muscles on the dorsal aspect of the body in prone of the adult subject of this study (NE 65 ± 15 ms, TE 67 ± 4 ms, TRIC 83 ± 9 ms, and EXC 61 ± 11 ms).

Two-Peaked EMG

In the Greenwood and Hopkins (2,9) studies of landing responses on the feet following unexpected release from hanging in a parachute harness, the EMG responses showed two peaks. The onset of the first peak of soleus activity was ascribed to the acceleration during downward fall, which was sensed by the otolith apparatus, inducing a startle-like response. In addition, an important component of the startle response is a rapid contraction of the eyelids. The first peak of the soleus EMG was absent when the subject
himself released the harness and was also absent in patients without labyrinthine function (9). A similar mechanism might be involved in the onset of the two-peaked EMG responses in the present study. I did not subject the infants to having a surface electrode on the orbicularis oculi muscle, but did so to the adult subject. The latency to the eyeblink response was consistently within 34 ± 7 ms and was in the same range as that reported by Wilkins and colleagues (11). The two-burst pattern of the response was particularly pronounced in the neck and trunk muscles of the infants as well as in the infant who had two experimental sessions and in the adult, suggesting that the first burst is a startle-like response triggered from the passive mechanical response of the head and arm.

The onset of the arm muscle activity was associated with the sudden change of cutaneous pressure, that is, deformation of the soft tissues of the body and sudden change of cutaneous contact between the wrist and the platform, which occurred during the acceleration phase of the head-down rotation and the deceleration phase of the head-up rotation (Figures 7 and 8). Since the latency to the onset of the neck muscles was similar following head-down and head-up rotation, it seems that neck muscle activity was not triggered from the sudden change of pressure between head and platform. More likely, both the utricular and the saccular maculae sensed the sudden head displacement in space during head-down or head-up rotation, and neck muscle onset might represent the vestibular-induced startle response (2,12). In both platform perturbation modes, neck muscle onset was related to the acceleration phase of the platform, which would indicate that it corresponded to decrease of cutaneous pressure between the head and the platform during head-down rotation and to increase of cutaneous pressure during the acceleration phase of platform head-up rotation.

All infants had in their EMG response, particularly in the arm muscles, a second burst of long duration and more or less pronounced peak. The second burst might be the early substrate of the landing response that is seen at a later age, rather than the continuation of a startle response. Following the line of thought that the startle response is a basic flexion reflex (for example, stereotyped alerting response independent of the type of sudden sensory input (13,14) and that the second burst in our study is also a part of the startle response, one would not expect that the triceps would be activated and the wrist kept on the platform during several hundred milliseconds of the burst. Further, latencies in muscles in response to startling auditory stimuli show an increase with segmental distance from the lower brainstem (15), and that was not the case in this study. The EMG recordings in this study showed a co-activation of wrist extensor and flexor (EXC, FLC) and to some extent also of elbow extensor, flexor muscles (Figures 2 and 5) for several hundred milliseconds. This seems not to be a characteristic of a startle response. Following head-up rotation, the elbow angle (Figure 2, Arm trace) increased with some amount of co-contraction between BIC and TRIC, and the wrist was kept on the platform, suggesting that the EMG activity and movement pattern are a part of a landing response. This assumption is further supported by the deflection in the elbow traces, as shown in Figure 8. While the wrist is kept on the platform, the elbow traces showed an upward deflection, indicating an extension in the elbow in the adult and also in the 13-week-old infant. The 2-week-old infant showed a similar tendency, although the slow upward deflection started about 500 ms after onset of the platform movement. Note, however, that the wrist did not deviate from the baseline.

Greenwood and Hopkins (2) pointed out that the second peak EMG response during sudden falls in adults is timed to landing and is concerned with the voluntary control of landing. Because infants were used in the present study, the second burst EMG would probably not be accounted for by a voluntary landing response. An alternative explanation is that the landing pattern is, like locomotion, an innate pattern (16) ordered under voluntary control in humans at a later age during motor development (17).

**Head Orientation**

In these experiments, the arching of trunk and neck were absent. As shown in the model in
Figure 7, the position traces of the head would go above the shaded area if arching were present. That the head was often below the initial position level after the platform perturbation probably depended on the infant's turning the head some degrees from the right towards the middle. One reason for lack of head lifting might be that the stimuli used in this study were too strong or too short in time to elicit lifting of the head. Another reason might be that lifting the head in response to sudden surface rotation in prone position (large support base) is not a functional goal-directed response to this stimulus. Head control might be focused primarily on the orientation of its position relative to the trunk and not to displacement in space. During landing on the ground after freefall, the impact on the feet or hands on the ground generates the ground reaction force accelerating the body mass against gravity. During landing on the hands, the triceps activity will extend the elbows and arch the trunk. Co-activity in neck extensors and flexors can control the head so that it follows the trunk movement. In all infants of 2 to 4 weeks, as well as in the 13-week and the adult control subjects, triceps activity was seen together with activity in the trunk extensor (TE-LE). Neck activity was weak in the 2- to 4-week-old infants. One might suppose that the initial position of the head turned to the right is not optimal for eliciting neck responses. However, on reassessment the 13-week-old infant's head was turned to the right and the neck EMGs were no longer weak. In addition, the adult had optimal conditions for neck activity, since he was lying with the head straight and the forehead supported on the surface, and yet the neck EMG had only medium responses. It may be that during falling the CNS primarily controls avoidance of collision of the trunk with the ground (arm extension, arching of the trunk), and the neck muscles control the alignment of the head to the trunk. In prone position, prerequisite for arching the trunk is a downward tilt of the pelvis (lumbar lordosis). Newborn infants tilted the pelvis backward during head-down rotation, aggravating arching the upper trunk, even though trunk and arm extensors were contracting. But since the trunk was not arching upward, head orientation to the trunk was unchanged and thus not demanding intense activity in neck muscles. The present results suggest that the substrate for the landing response is present in pathways controlling the arm muscles at this age, but the strength cannot yet be generated for pushing the upper trunk upwards.

In the present experimental setup, the "impact" phase was thought to be mimicked by the head-up rotation of the platform. The fact that in infants the onset of arm muscle activity was not related to the acceleration of the platform toward the body (head-up rotation) suggests that the experimental design was suitable for mimicking falls, but not landings.

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