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Postural adjustments in catching: on the interplay between segment stabilization and equilibrium control

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RUNNING HEAD: Postural adjustments in catching

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Running head: POSTURAL ADJUSTMENTS IN CATCHING

**Postural adjustments in catching: on the interplay between segment stabilization and
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Abstract

The purpose of this study was to investigate postural adjustments in one-handed ball catching. Specifically, the functional role of anticipatory postural adjustments (APA) during the initial arm raising and subsequent postural adjustments (SPA) for equilibrium control and ball-hand impact were scrutinized. Full-body kinematics and kinetics allowed an analysis of the mechanical consequences of raising up the arm and preparing for ball-hand impact. APA for catching were suggested to be for segment stabilization. SPA had a functional role for equilibrium control by an inverted pendulum mechanism but were also involved in preparing for the impact of the ball on the hand, which was illustrated by an increased postural response at the end of the movement. These results were compared with raising up the arm in a well-studied reaction-time task, for which an additional counter rotation equilibrium mechanism was observed. Together, our findings demonstrate that postural adjustments should be investigated in relation to their specific functional task constraints, rather than **generalizing the functional role of these postural adjustments** over different tasks.

Key Words

Postural adjustments; Catching; Arm raising; Segment stabilization; Equilibrium control

Postural adjustments in catching: on the interplay between segment stabilization and equilibrium control

Introduction

Catching an approaching object while standing (e.g., cricket fielding, handball) demands postural control related to raising the arm upwards and towards the object, as well as the subsequent postural disequilibrium caused by the expected and actual mechanical impulse of the ball acting on the hand. However, despite there being extensive study of how the human perceptual-motor system is organized during catching (Zago, McIntyre, Senot, & Lacquaniti, 2009), less attention has been paid to the role that postural control might play during such actions. At a behavioral level, the relevance of this omission is evident in the finding that postural control can be decisive for successful catching performance. For example, performance in poor catchers was found to approach the level of good catchers when sitting or with the aid of a support (Davids, Bennett, Kingsbury, Jolley, & Brain, 2000; Angelakopoulos, Davids, Bennett, Tsorbatzoudis, & Grouios, 2005; Savelsbergh, Bennett, Angelakopoulos, & Davids, 2005). Further, in the somewhat less disequilibrating task of catching a falling object while standing, it has been shown that prior to moving the relevant effectors for prime arm movement, there is an anticipatory muscle contraction in muscles that are responsible for postural control (Shiratori & Latash, 2001; Li & Aruin, 2007, 2009). To date, however, while it is understood that postural adjustments associated with prime arm movement (i.e., vertical raising) are attributable to different control mechanisms (see below for more detail), a comprehensive conceptual understanding of such mechanisms during the interception of an approaching object has yet to be reported.

The existence of anticipatory postural adjustments (APA) has been observed in a task relatively similar to catching an approaching object, where the participant raises the arm vertically from beside the hip to the horizontal forward position. When raising the arm while standing, body posture is disturbed as the moving arm causes a quick change of the body geometry, which leads to a forward acceleration of the segment centre of mass (COM). The internal forces caused by this acceleration of the prime mover in turn result in destabilizing reaction forces on the supporting segments (Massion, 1992). To counteract the destabilizing consequences of these forces, the central nervous system is suggested to exhibit APA (Bouisset & Zattara, 1987; Zattara & Bouisset, 1988), which is believed to occur simultaneously with, or just before, the initiation of the voluntary movement by means of feedforward control (Cordo & Nashner, 1982). For raising one or both arms as a reaction to an auditory or visual stimulus, the mechanical expression of APA has been reported as a backward shift of the centre of pressure (COP) starting before movement onset (Aruin & Latash, 1995; Hodges, Cresswell, & Thorstensson, 1999; Cuisinier, Olivier, & Nougier, 2005; Bleuse et al., 2006; Bleuse et al., 2008).

While early postural responses have most frequently been associated with an inverted pendulum acting at the level of the ankle, which generates anticipatory forward acceleration of the whole body COM to compensate for the ensuing inertial forces from prime mover motion, a comparison of model-based and experimental data has led to the suggestion that the initial postural **motion** of whole body COM is in fact passive and hence that APA are better explained as a side effect of local segment stabilization (Pozzo, Ouamer, & Gentil, 2001; Patla, Ishac, & Winter, 2002). Segment stabilization is needed to counter reactive torques from the arm acting on the shoulder, which in turn affect the hip, knee and ankle joints. This means that after the initial movement impulse and its disequilibrating effects, subsequent postural adjustments (SPA) are required to maintain whole body postural equilibrium. In

1 addition to the inverted pendulum mechanism acting at the ankle, a potential counter-rotation
2 mechanism exists, which acts primarily at hip-level and is often required to retain balance in
3 more destabilizing situations (Hof, 2007). This mechanism involves increased horizontal
4 ground reaction forces (GRF), which generate linear accelerations of the whole body COM,
5 and is thus distinct but complimentary to the inverted pendulum mechanism and the resulting
6 torque generation at the ankle. Indeed, the counter-rotation mechanism rotates the GRF
7 vector, whereas the inverted pendulum mechanism translates the GRF vector.

8 Putting aside recent debate on the functional role of observations identified as APA
9 (Pozzo et al., 2001; Patla et al., 2002), their presence and subsequent SPA have been well
10 described in reactive arm raising tasks. This has provided a useful baseline for understanding
11 postural adjustments in arm raising tasks, but as alluded to above there are important
12 differences compared to one-handed catching, which could influence the mechanisms involved
13 in maintaining postural balance. Raising the arm in reaction to an external stimulus demands a
14 relatively simple and internally-timed intra-limb coordination, whereas one-handed catching
15 requires a precise spatiotemporal coordination between the catching arm and approaching ball
16 in order to bring the catching hand to the right place at the right time (Tijtgat, Bennett,
17 Savelsbergh, De Clercq, & Lenoir, 2010). Therefore, in addition to countering disequilibrium
18 due to raising the arm, one-handed catching often involves a reversal of the forward
19 displacement of the arm in order to reduce impact at ball-hand contact to controllable levels
20 (Williams & McCririe, 1988). This can be expected to influence SPA, with the latter task
21 potentially involving the two complementary equilibrium control mechanisms (i.e., inverted
22 pendulum and counter rotation). Here, then, we report a study that was designed to
23 comprehensively evaluate postural adjustments in one-handed catching, and thereby the
24 contribution of APA and SPA, using mechanical observations.

Method

Participants

Six male self-declared right handed participants (aged between 21 and 23, mean weight 74.9 ± 7 kg and mean height 180.3 ± 4 cm) gave their written informed consent (approved by the Ethical Committee of the host University) before participating.

Materials and procedure

Participants were asked to stand still with their feet parallel (two marked lines) on a force plate (AMTI, 1000 Hz), arms besides the body and head upright with the gaze **directed** forward. The experiment consisted of 10 catching trials (CATCH). Participants were instructed to catch yellow, mid-pressured tennis balls. At the completion of the movement, the end position was retained for more than 3 seconds so that a new equilibrium-position was established. Balls were launched at a speed of 15.8 ± 0.16 m/s at 8.4 m from the participant's frontal plane by a ball-projection machine (Promatch/Mubo B.V., Gorinchem, The Netherlands). The machine was covered with black plastic that had a small cut-out section through which the balls were released so that participants could not anticipate ball delivery. Launching angle was adjusted so that balls arrived above participant's right shoulder. Spatial standard deviation of the interception point was 4.40 cm in the medio-lateral and 7.61 cm in the vertical direction (reflective of the variability of the ball machine); and 7.86 cm in the anterior-posterior direction as a result of the interaction between ball trajectory and forward movement of the hand. After catching, participants performed a reaction-time action (RAISE). They were instructed to raise their right arm as fast as possible until horizontal from the moment they saw a ball coming out of a ball machine. For RAISE, launching angle was changed so that while balls were still delivered towards the participant, they could not reach

the participants' body. Participants wore headphones that minimized sound generated by the ball machine and a face shield to protect the face, while not disturbing access to the full visual field. Three-dimensional kinematic data were collected at 200 Hz using 12 infrared cameras (Proreflex, Qualisys AB, Gothenburg, Sweden). Markers were bilaterally placed on distal phalanx of hallux and digitus minimus, lateral and medial aspect of calcaneus, malleolus and femoral condyles, iliac crest, anterior and posterior superior iliac spine, sternum, C7, intertubercular sulcus of humerus, styloid process of radius and ulna, distal phalanx of thumb and index.

Data processing

Kinetic and kinematic data were recorded simultaneously and filtered (low-pass Butterworth filter at 20 Hz for kinetics and at 10 Hz for kinematics). A 14-segment model consisting of feet, shanks, thighs, pelvis, thorax/abdomen, upper arms, lower arms and hands was developed using Visual 3D (C-Motion Inc., Gaithersburg, MD, USA).

Flexion and extension angles were calculated for elbow, shoulder, hip and ankle and expressed relative to their baseline level (between 500 and 300 ms before movement onset). COP anterior-posterior displacement was also expressed relative to the average position between 500 and 300 ms before movement onset. Onsets were calculated according to the criterion that the acceleration of the signal had to exceed 0.5 m/s^2 for at least 25 ms. Onset of arm movement (t_0) was derived from the forward acceleration of the wrist. Onset of postural adjustments was derived from the anterior or posterior acceleration of COP. Movement time (MT) was the time between t_0 and the end of the deceleration phase (t_{end}).

The effect of raising the arm was quantified for both tasks by calculating COM-displacement and changes in momentum of key segments of the moving body. COM and momentum of the whole body (body), the right arm (consisting of right upper arm, lower arm

and hand) and of the body without the right arm (rest of body), were derived. Finally, flexion and extension angles of hip and ankle together with resultant anterior-posterior COP-displacement and ground reaction forces (GRF) were included to enable a conclusive analysis of the equilibrium control mechanisms as suggested by Hof (2007).

Statistical Analysis

Intra-participant mean data from 10 successful trials for CATCH and RAISE were calculated. Due to the small sample size, statistical tests consisted of non-parametric Wilcoxon tests. The level of significance was set at $p < .05$.

Results

Arm movement

The catching movement (CATCH) was recognized by substantial elbow flexion (45 ± 4 deg) at t_0 that preceded shoulder flexion (Fig. 1). As a consequence, the forward displacement of the COM of the arm was 10 cm less forward as compared to RAISE ($z = -2.207$, $p < .05$), notwithstanding a comparable acceleration-deceleration profile of the wrist, though with more prominent peak amplitudes in RAISE ($z = -2.207$, $p < .05$).

APA

With respect to the mechanical observation of APA, no clear backward shift in COP before t_0 was observed. Onset of COP-shift was reached on average at 23 ± 45 ms (CATCH) and 3.33 ± 48 ms before t_0 (RAISE), and was not significantly different between conditions ($z = -1.363$, *ns*).

Raising the arm for catching resulted in a similar forward displacement of arm COM and forward change in arm momentum (Fig. 2). This was compensated by a backward displacement of COM of the rest of the body, and an opposing momentum of the rest of the body that closely matched the arm movement. The net result of the interplay between the displacements of arm and rest of body was a forward displacement of the whole body COM (Fig. 2).

SPA

Shortly before ball-hand contact, the arm was moved backward in anticipation of ball impact, resulting in a backward change of momentum of the arm (Fig. 2). This was **preceded** by a forward change in momentum of the rest of the body that was larger for CATCH than for RAISE ($z = -2.207, p < .05$). The net result of this interplay between postural control for arm raising and grasping was a sustained forward momentum of the body.

An initial forward GRF was followed by a slight hip flexion and a backward GRF (Fig. 3). The hip was extended in the second part of the catching phase and led to increased forward GRF. At the ankle joint, a small plantar flexion in the ankle and a forward shift of COP was observed, followed by dorsiflexion and COP that returned backward (Fig. 4). As compared to CATCH, the RAISE task was characterized by a clear dynamic hip flexion and extension movement. As a consequence, the initial posterior GRF changed rapidly to a forward GRF, followed again by a backward GRF (Fig. 3). Plantar flexion in the ankle was also observed, together with a COP that was initially shifted forward, albeit with a backward return followed by forward shift near the end of movement (Fig. 4).

Discussion

The present study evaluated in one-handed catching the presence of APA with its role for segment stabilization or primary equilibrium control, and SPA with its role for equilibrium control and countering ball impact effects. One-handed catching did not exhibit consistent APA involving backward COP shifts prior to arm movement onset. Early postural adaptations supported the notion of segmental stabilisation more than equilibrium control. The observed SPA leading up to ball contact supported both proposed equilibrium control mechanisms, involving postural modification associated to ball impact. We will consider each of these aspects in the light of previous studies, and where relevant provide supportive or countering argumentation from the comparison with reactive arm raising.

APA prior to movement onset

The presence of APA has typically been evidenced by a consistent backward shift of COP-displacement before t_0 (Aruin & Latash, 1995; Hodges et al., 1999; Cuisinier et al., 2005; Hirschfeld, 2007; Girolami et al., 2010; Aimola et al., 2011), and has been represented by mean values from single representative subjects. In this experiment, however, no representative subject could be selected. On the contrary, our results showed large intra- and inter-subject variability in COP-displacement at t_0 (see Fig. 5), with backward and forward shifts, as well as no shifts. Other studies have also failed to show a consistent backward movement of the COP before movement onset (De Wolf, Slijper, & Latash, 1998; Nougier, Teasdale, Bard, & Fleury, 1999; Hay & Redon, 2001; Ferry, Martin, Termoz, Cote, & Prince, 2004; Mochizuki, Ivanova, & Garland, 2004). While such variability has rarely been reported in literature on APA in arm raising, it is notable that there is some suggestion from work on catching a falling ball with an outstretched arm that “signals obtained from force plate showed large variability across subjects” (Shiratori & Latash, 2001, p. 1251). A potential explanation

for the lack of finding APA clearly prior to movement onset in catching may be the presence of elbow flexion observed, since raising the arm when the elbow is flexed involves less destabilization (van der Fits, Klip, van Eykern, & Hadders-Algra, 1998; Bleuse et al., 2006; Bleuse et al., 2008). Nevertheless, also in the RAISE task, where considerably less elbow flexion took place than during catching, no consistent APA prior to movement onset was observed (Fig. 5, right panel), which seems in conflict with some suggestions made in the literature. Taken together, our findings indicate that the proposed backward shift of COP before movement onset is not a ubiquitous indicator of APA, and that if APA is considered present its functional role for whole body equilibrium control should be questioned (Pozzo et al., 2001; Patla et al., 2002). The initial motion of whole body COM might be a passive consequence of reaction forces due to counter-rotating segments rather than an active control of postural equilibrium, with antagonistic co-activations for segment stabilization. The generation of whole body forward momentum was up to 0.04 kg.m/s. Considering that less forward momentum was observed in RAISE, strengthens the argument that successful catching and supportive segment stabilization is prioritized over equilibrium control during APA.

SPA for equilibrium control

After initial segment stabilization, an inverted pendulum strategy at the level of the ankle was found to be the predominant postural strategy for the catching movement (Hof, 2007), with angular displacement at the ankle explaining the COP-shifts. This supports the notion that active equilibrium control of the whole body COM occurs only 200 ms after t_0 (Patla et al., 2002). Due to segment stabilization, the hip joint was only marginally flexed, followed by a hip extension and continued forward momentum of the rest of the body. This would be counter intuitive in the light of equilibrium control, but seems indicative of a

postural control mechanism to anticipate the ensuing impact of the ball at the hand. In comparison, for RAISE a larger and dynamic hip flexion-extension coupling suggests an additional counter-rotating mechanism at hip level in addition to the inverted pendulum mechanism (Hof, 2007). Despite larger changes in momentum of the arm, the forward momentum of the rest of the body at t_{end} , was 34% less than in CATCH where a ball impact was evident around this time. Clearly, these differences in postural control between both tasks indicate that postural adjustments to voluntary movements are closely related to specific task constraints (see also Ilmane & LaRue, 2008). Future work could reveal how postural adjustments might differ between different spatial or temporal constraints during interceptive actions.

Finally, some limitations of the present study have to be acknowledged. This study was limited to a sagittal plane analysis only considering the anterior-posterior direction of movement. Accordingly, axial rotations that could influence equilibrium control during unilateral arm raising were not analyzed (Bouisset & Zattara, 1987). Also, the observed findings only allow to suggest possible postural control strategies. A future in depth analysis through forward dynamic simulations could establish the true causative nature between reaction forces due to the prime mover and concomitant postural adjustments.

Conclusion

During arm raising for unconstrained catching, initial postural adjustments by feedforward control seem to be a consequence of the inertia of the movement itself (segment stabilization), rather than a mechanism to immediately counter disequilibrium. Afterwards, an inverted pendulum mechanism accommodates equilibrium control when raising the arm for

1 catching, whereas increased postural control seems to be warranted in preparation of ball
2 impact on the hand. When raising the arm in a simple reaction-time task, SPA by an inverted
3 pendulum was observed but with an additional counter-rotating mechanism to maintain
4 balance. Overall, our findings demonstrated that the spatio-temporal constraints of one-
5 handed catching lead to postural adjustments specific for that task, notwithstanding that both
6 CATCH and RAISE disturb body posture in a similar way by raising the arm.

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4

Figure Captions

Figure 1.

Acceleration of wrist, angular displacement of elbow and shoulder, and displacement of COM of arm for CATCH (left panel) and RAISE (right panel). Group mean data and its standard deviation (dashed lines) are presented. First vertical line is t_0 , second vertical line is t_{end} .

Figure 2.

Arm, body and rest of the body displacement of COM and momentum for CATCH (left panel) and RAISE (right panel). Group mean data and its standard deviation (dashed lines) are presented. First vertical line is t_0 , second vertical line is t_{end} .

Figure 3.

Counter-rotating mechanism. Stick-diagram of participant DM. Group mean data and standard deviation (dashed lines) of the angular displacement of hip and displacement of GRF for CATCH (left panel) and RAISE (right panel). First vertical line is t_0 , second vertical line is t_{end} .

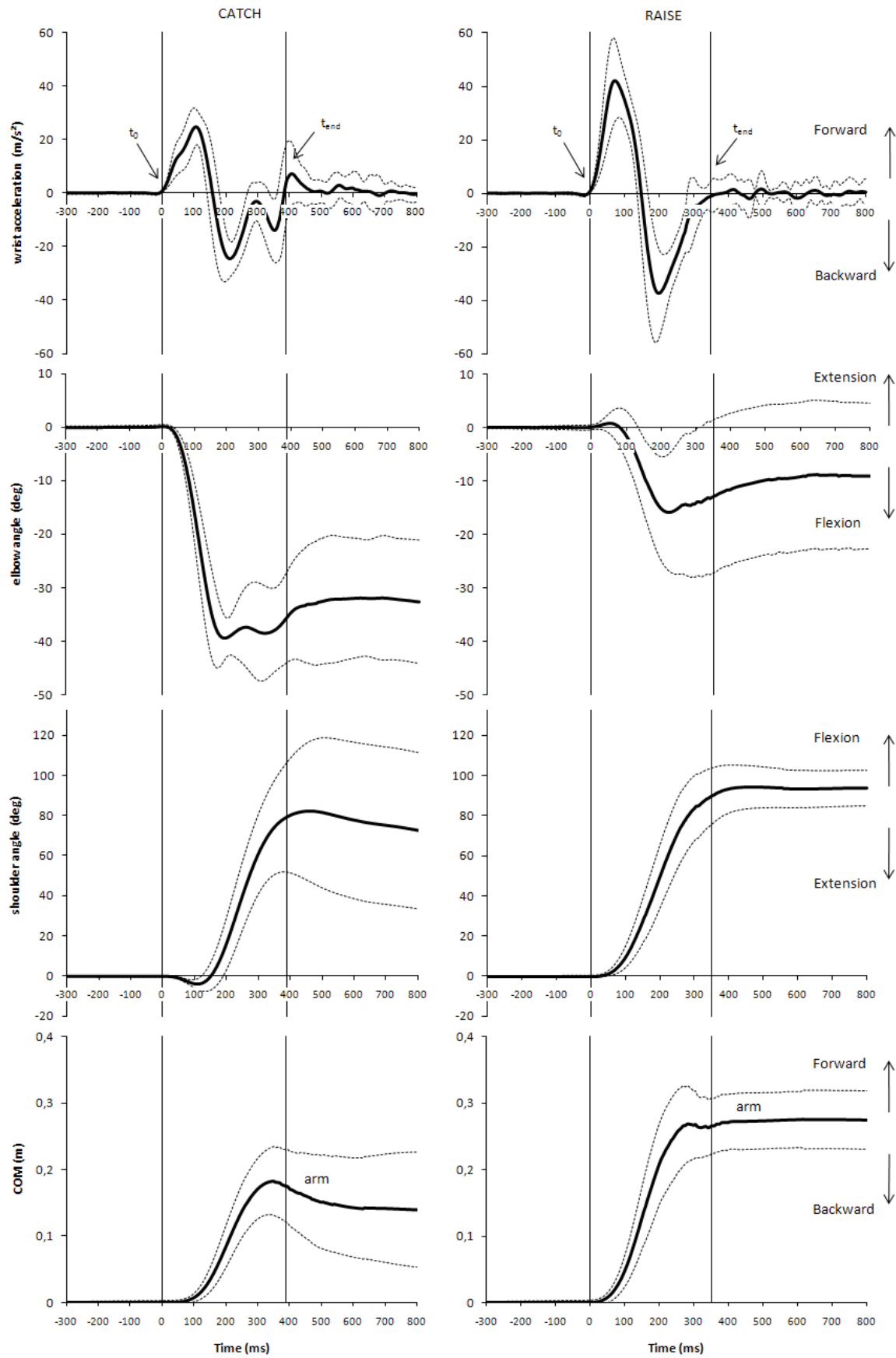
Figure 4.

Inverted pendulum mechanism. Stick-diagram of participant DM (rotation at the hip segment is abandoned). Group mean data and standard deviation (dashed lines) of the angular displacement of ankle and displacement of COP for CATCH (left panel) and RAISE (right panel). First vertical line is t_0 , second vertical line is t_{end} .

Figure 5.

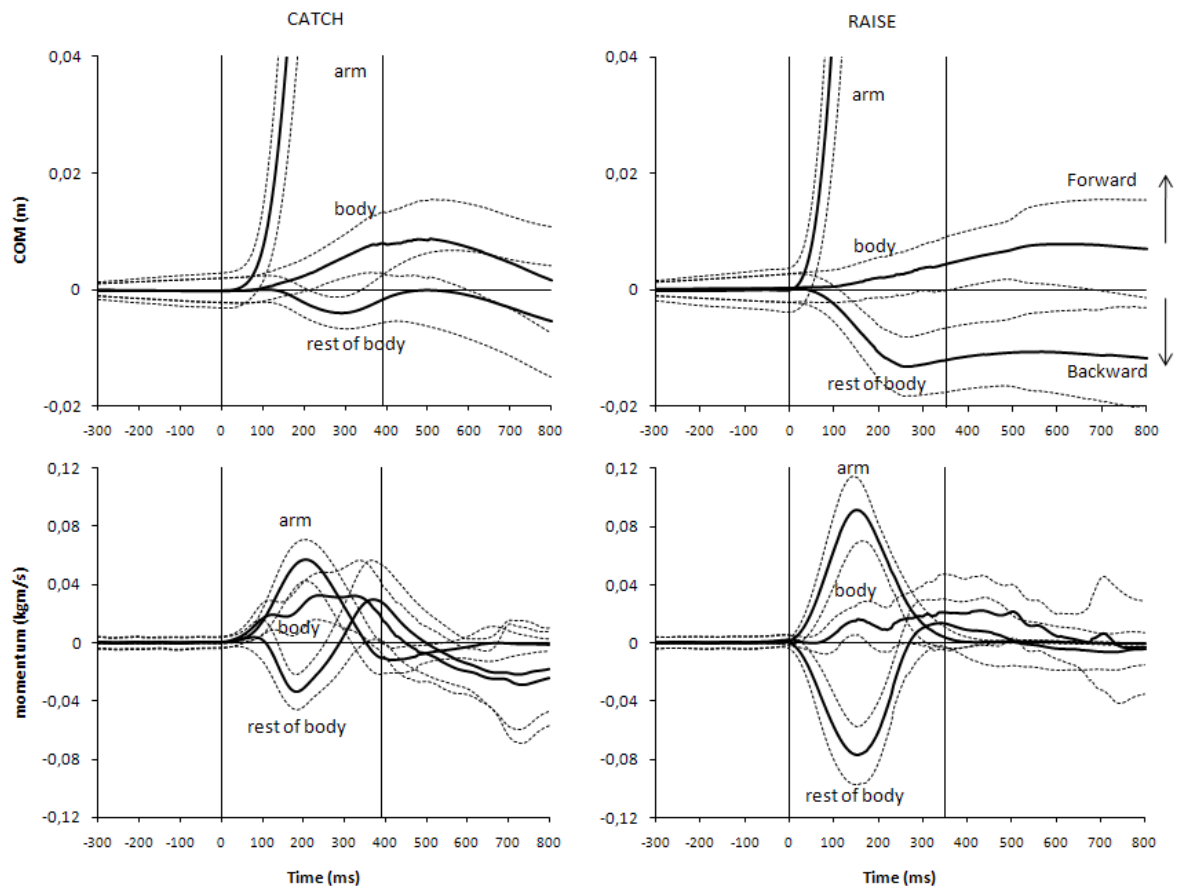
- 1 COP-displacement traces for CATCH (left panel) and RAISE (right panel) around t_0 . All
- 2 trials for all subjects are represented. Onset of COP is indicated with ticks. Vertical line is t_0 .

1 Figure 1.



1

2 Figure 2.

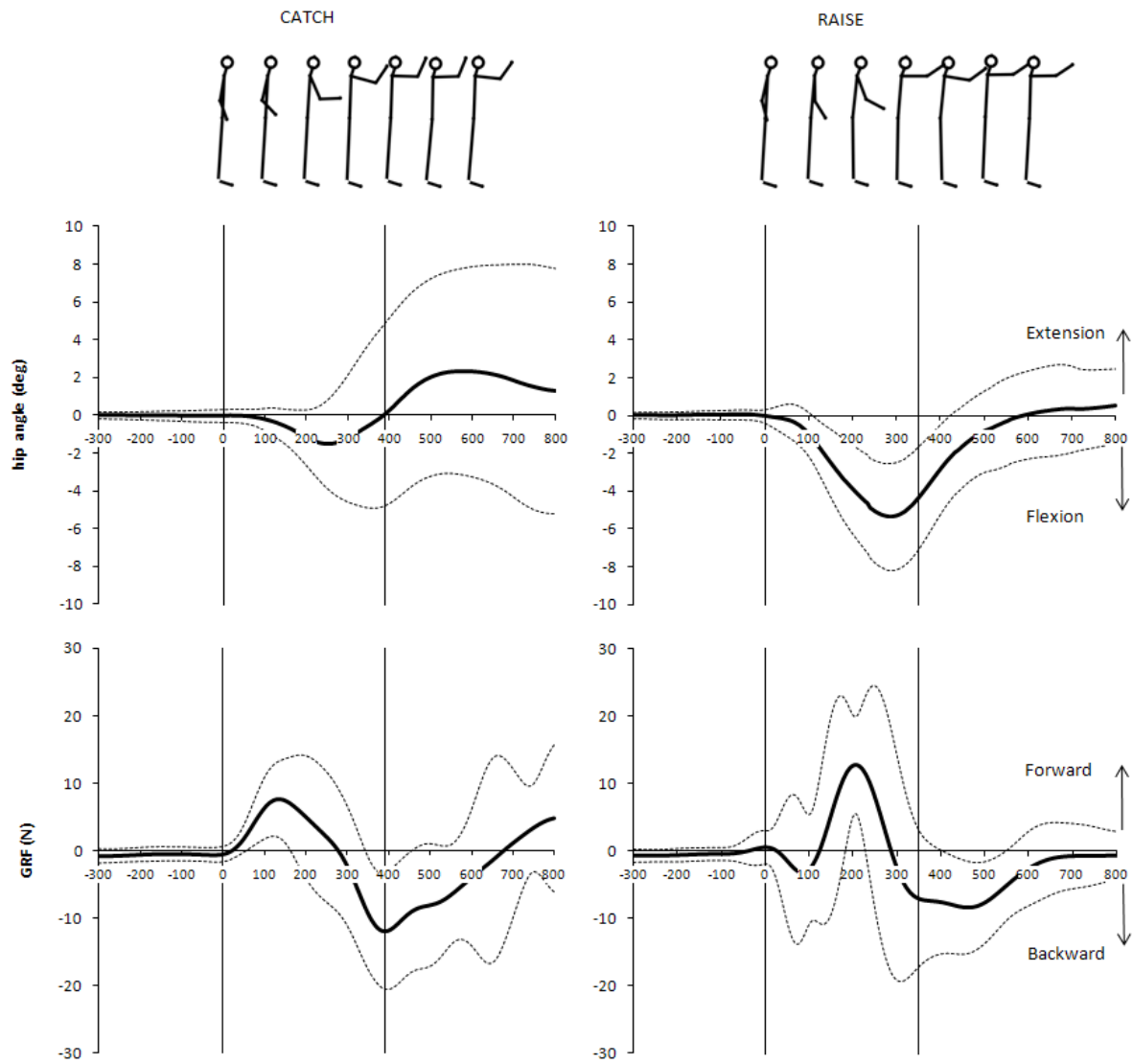


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2 Figure 3.



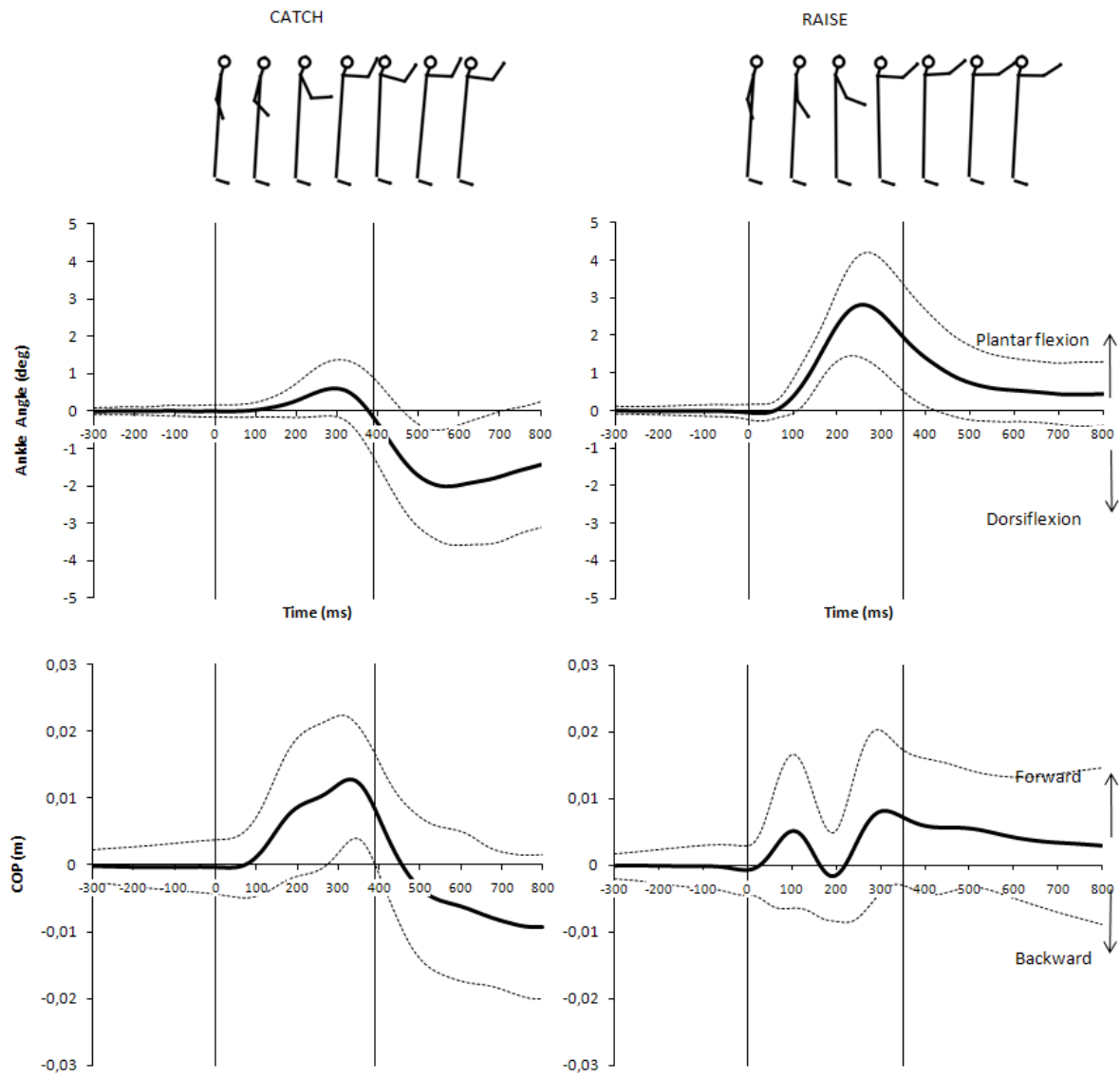
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2 Figure 4.



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Figure 5.

