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The effects of time pressure and experience on the performance of fall techniques during a fall

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Abstract

Although the practice of fall techniques has been introduced in fall prevention programs, it is not clear whether people can apply acquired techniques during a real-life fall. It would be helpful to know the time it takes to initiate and to successfully execute such techniques, as well as the effect of experience on the execution of these techniques. In this study we investigated the neuromuscular control of voluntary fall techniques in five seasoned judokas and nine non-judokas. After they had started falling from a kneeling position, they received an auditory cue prompting either a lateral natural fall arrest (block) or a martial arts (MA) fall. EMG data of shoulder and trunk muscles were collected. The requested technique was successfully applied in 85% of the falls. Following the cue, EMG amplitudes of the fall techniques started to diverge after 180-190 ms. EMG amplitudes were generally similar in both groups, but experience-related differences could be demonstrated in the pectoralis and trapezius. In conclusion, voluntary motor control is possible within the duration of a fall, even in inexperienced fallers. Differences in EMG activity might suggest that experienced fallers changed their reaction to possible falls from a preparation for arm abduction into a preparation for trunk rotation.

Keywords: Human falls; Fall technique; Electromyography; Muscle activation

1. Introduction

Falling is the leading cause of injury-related death in adulthood (Kannus et al., 2000). It is therefore essential to understand the motor control of falls. How do humans react during a fall and how much can they change their behavior prior to hitting the surface? This type of questions has been studied using falls from standing or from kneeling height. For falls from standing height most studies use a paradigm of tether release (Do et al., 1990; Do and Roby-Brami, 1991; DeGoede and Ashton-Miller, 2002; Lo et al., 2003; Robinovitch et al., 2003) but some use a functional reach test (Ahmed and Ashton-Miller, 2007) or voluntary initiated falls (Van den Kroonenberg et al., 1996). It was shown that voluntary modification of a fall is possible and that a proper fall arrest strategy can affect peak impact at contact (DeGoede and Ashton-Miller, 2002; Robinovitch et al., 2003). A similar conclusion was reached from studies using falls from a kneeling position (Sabick et al., 1999; Groen et al., 2007). Sideways falls are the most intensively investigated because hip fracture risk is increased when falling sideways (Parkkari et al., 1999), especially when the hip is impacted (Kannus et al., 2006; Schwartz et al., 1998). Therefore, strategies to prevent fall-related hip fractures should not only target at decreasing the frequency of fall incidents but also at the severity of these falls to the side.

Several fall strategies to reduce fall severity of sideways falls have been studied including martial arts (MA) fall techniques (Groen et al., 2007; Sabick et al., 1999). MA fall

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techniques (derived from judo) could reduce hip impact forces in sideways falls by 12–27% in experienced martial artists (Groen et al., 2007; Sabick et al., 1999). Recently, it was shown that a 30-min training in MA fall techniques was sufficient to reduce hip impact forces by 15% in young adults without prior experience in martial arts (Weerdesteyn et al., 2007). In these studies a verbal cue was given after initiation of the fall, indicating which fall technique had to be performed. Hence, the resulting differences in impact forces showed that it was possible to initiate and thus change fall strategies after the start of a fall. Similarly, Feldman and Robinovitch (2004) conducted an experiment in which either forward or backward axial body rotations were visually cued at various instants both before and after fall initiation. It was found that a critical time window of 200 ms existed following the start of a fall, within which the movement to arrest the fall should be initiated in order to be effective. However, because fall durations were not reported, it remains unclear how much time was left after this critical time window, to initiate and successfully execute the requested technique.

To our knowledge, no previous study has been performed to determine how voluntary movements during a fall are controlled at the neuromuscular level, in terms of reaction times and muscle activation patterns. Therefore, it is also unknown whether the characteristics of neuromuscular control would be susceptible to time pressure. In a previous study, muscle activity in automated reactions, like stepping to regain balance, was found to increase with increasing time pressure (Thelen et al., 2000). In addition, Wang et al. (2006) found that in self-paced stepping, EMG amplitudes were significantly larger and showed higher rates of change during very quick steps compared to comfortably paced steps. Therefore, it may be expected that muscle activation amplitudes increase in fall strategies, in order to generate a more vigorous action when there is only a short time until landing.

Furthermore, although a previous study has shown that MA techniques can be used to reduce hip impact forces after a short training (Weerdesteyn et al., 2007), it is still unknown whether the performance, in terms of EMG characteristics, equals that of experienced fallers. For several sports it has been shown that detailed analyses of given movements can distinguish between experienced athletes and novices (Zehr et al., 1997; Harmenberg et al., 1991). Such analyses can give insight into the differences in motor planning (Yiou and Do, 2001). Furthermore, knowledge of experience-related differences in the neuromuscular control of fall techniques could help to set specific targets to optimize the benefits of training.

The aim of the present study was to examine the neuromuscular control of fall techniques during a sideways fall. Two research questions were determined. The first question was how much time it takes to initiate and to adequately perform such techniques. Secondly, we aimed to determine whether years of experience in fall techniques would have an effect on performance, in terms of success rates and EMG characteristics. To answer these questions the following experiment was conducted. In a choice reaction task to an auditory cue, one of two fall techniques had to be performed during a fall. One technique was a natural fall arrest strategy with an outstretched arm into the direction of the fall; the other technique was an MA fall, which is characterized by rolling on over the trunk after impact. The cue was given at different delays after the start of the fall. The successfulness on the task was assessed by two independent observers. Muscle activation patterns of the two techniques were determined, as well as reaction times to the cue. Reaction time was defined by the instant at which muscle activation patterns started to differ between techniques. Finally, muscle activation patterns of experienced and inexperienced fallers were compared in order to evaluate the effect of extensive training on timing, amplitude and patterning of EMG responses.

2. Methods and materials

2.1. Participants

A total of 14 healthy young women (aged 21–35) participated; 5 participants were seasoned judokas (experienced group, 19–25 years of judo experience) and 9 were inexperienced in any fall technique (inexperienced group). None of the participants suffered from any neurological or musculoskeletal disorder that could affect their performance and/or behavior in this study. The Ethical Board of the region Arnhem-Nijmegen approved the protocol, and participants gave informed consent to participate.

2.2. Experimental setup and protocol

The experimental setup consisted of a 2.2 by 2.7 m platform, covered with judo mats (4 cm polyurethane foam, Agglorex®, Lommel, Belgium). The participants were kneeling on the platform. They held on to a grip with the extended right arm, such that the lateral inclination of the trunk and upper legs was 21°, relative to the vertical. (see Fig. 1).

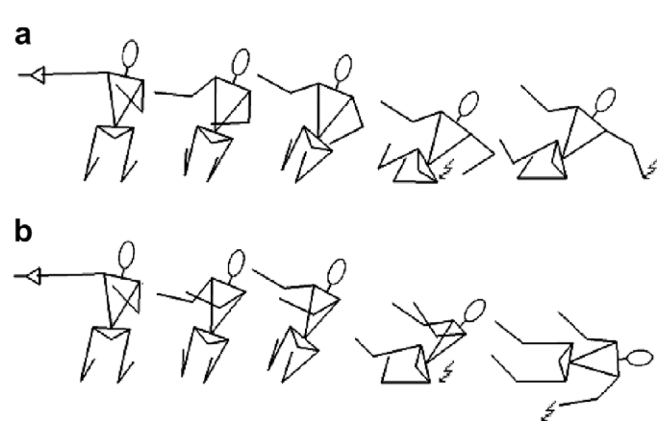

Fig. 1. Schematic representation of fall techniques. In the starting position subjects held on to a grip with the extended right arm: (a) block fall technique and (b) MA fall technique. Impact is indicated by a broken arrow.

The participants received a vocal command to release the grip. The moment of release was detected by a load switch, placed in series with the grip. After release, participants started falling to the left and during the fall they received one of two auditory cues, one at a low pitch (500 Hz) or one at a high pitch (3000 Hz). The low pitch cue indicated that a natural fall arrest strategy was required, characterized by stretching out the left arm into the direction of the impending fall in combination with trunk lateral flexion in opposite direction (Allum et al., 2002; Groen et al., 2007). This technique, in which the fall was blocked with the arm, will be referred to as the block technique (Fig. 1a). The high pitch cue indicated that a martial arts fall technique (MA), derived from judo was required. This technique is characterized by trunk lateral flexion in combination with trunk rotation and shoulder protraction in order to enable rolling on after impact (Groen et al., 2007; Weerdesteyn et al., 2007) (Fig. 1b). The auditory cue was delivered at three delays after release, 1, 40 or 80 ms, yielding six experimental conditions (two techniques at three delays). To familiarize to the task, each participant performed 20 practice trials. During the experiment, the participants performed five trials of each of the six conditions, randomly divided over one series of 30 trials. Finally, one catch trial without auditory cue was included at the end of the protocol. Two independent observers judged during the experiment whether the required technique had been performed successfully. They agreed in 100% of cases. Successful execution of a block fall was defined as consecutively impacting the hip and the left hand or elbow without rolling on after impacting the left arm. Execution of the MA fall was successful when the subject rolled on after hip impact and the left arm was either not impacted or slapped on the mat after hip impact. Electromyographic recordings (EMG) were obtained from the left trapezius (TR), deltoideus pars posterior (DP), deltoideus pars anterior (DA), pectoralis (PE) and from the left and right obliquus abdominus (OA) and sternocleidomastoideus (SC) muscles, using self-adhesive electrodes (Ag/AgCl) (Conmed Neotrode®) placed approximately 2 cm apart and longitudinally on the belly of the muscle. EMG signals were pre-amplified and analog band-pass filtered (10-500 Hz). EMG data were sampled synchronously with the load switch at 2400 Hz and stored on a microcomputer.

2.3. Data analysis

For each participant and each condition, success rates were determined, as defined by the percentage of correctly performed trials. EMG signals were first processed by bidirectional high pass filtering (fourth order Butterworth filter; 15 Hz) to remove motion artefacts. To remove electrocardiographic (ECG) interference from EMG records of PE, and for some participants of OA as well, the ECG frequencies were isolated by low-pass filtering (50 Hz) and then subtracted from the signal. Subsequently, records of all the muscles were Hilbert transformed, full wave rectified, and bidirectionally low-pass filtered (fourth order Butterworth filter; 25 Hz) to acquire an adequate 'linear envelope' of the signal. The mean reference EMG activity was computed over 20 trials during 1 s of quiet hanging before fall initiation for each participant and for each muscle. EMG signals in response to the auditory cue were normalized with respect to this reference activity.

An example of normalized EMG signals of one muscle, during one trial of each technique is provided in Fig. 2a. For each participant, each muscle, and each condition, mean normalized EMG amplitudes were computed for 30 bins of 10 ms following the cue. Fig. 2b illustrates how mean normalized EMG amplitudes were calculated for an MA condition and a block condition. The overall mean fall duration was 405 ms. Given the maximum cue delay of 80 ms, the 30 bins following the cue include EMG activity during the fall, prior to impact.

To control whether subjects postponed fall arrest-related muscle activation until the cue, EMG amplitudes were also computed in the 150 ms period (15 bins of 10 ms) following release of the grip. In this period, cue-related activation was not expected for any of the cue delays, assuming that 150 ms is the minimum time limit in choice reaction tasks (Carson et al., 1995).

2.4. Statistical analysis

Multivariate analyses of variance (MANOVA) for repeated measures were used for statistical analysis of success rates and EMGs of the eight muscles. Group (experienced or inexperienced) was used as a between-subjects factor. Within-subjects factors were fall technique (block or MA), delay condition (1, 40, and 80 ms), and bins of EMG activity. With respect to the latter factor, 30 bins following cue were included in the analysis of the cue-related (and thus technique specific) effects. In the analysis of release-related EMG activity, 15 bins following release were included. Post-hoc deviation contrasts were determined to differentiate between the delay conditions. To detect the first bin after the cue in which significant differences in EMG activity between the techniques occurred (point of divergence), post-hoc reverse Helmert contrasts were used. An additional criterion for the determination of this point of divergence was that the difference between the techniques had to remain significantly different for four subsequent bins. This criterion was defined as a significant main effect of technique in an additional MANOVA for the four bins following the point of divergence. To analyze the strategies used to arrest the fall in the catch trial, a binomial test was applied. The alpha level was set at .05 for all tests.

3. Results

3.1. Success rates

Participants successfully performed the requested technique in 85% of the falls. Table 1 shows the means and standard deviations of fall technique success rates of all participants for each condition.

Success rates did not differ between the experienced and inexperienced fallers (main effect of group, $F(1,12) = .643$, $p = .438$, $\eta_p^2 = .051$), nor between the Block and MA technique (main effect of technique, $F(1,12) = .188$, $p = .673$, $\eta_p^2 = .015$). Success rates were significantly affected by the cue delay (main effect of delay, $F(2,12) = 6.983$, $p = .004$, $\eta_p^2 = .368$). Post-hoc contrasts revealed that participants were more successful in trials with cue delays of 1 ms and 40 ms than in trials with cue delays of 80 ms ($p = .003$, $\eta_p^2 = .529$ and $p = .034$, $\eta_p^2 = .322$, respectively). Experience in MA techniques did not affect the success rates in the six experimental conditions, as indicated by the absence of significant interactions between technique and group and between group and delay (all p values $>.129$).

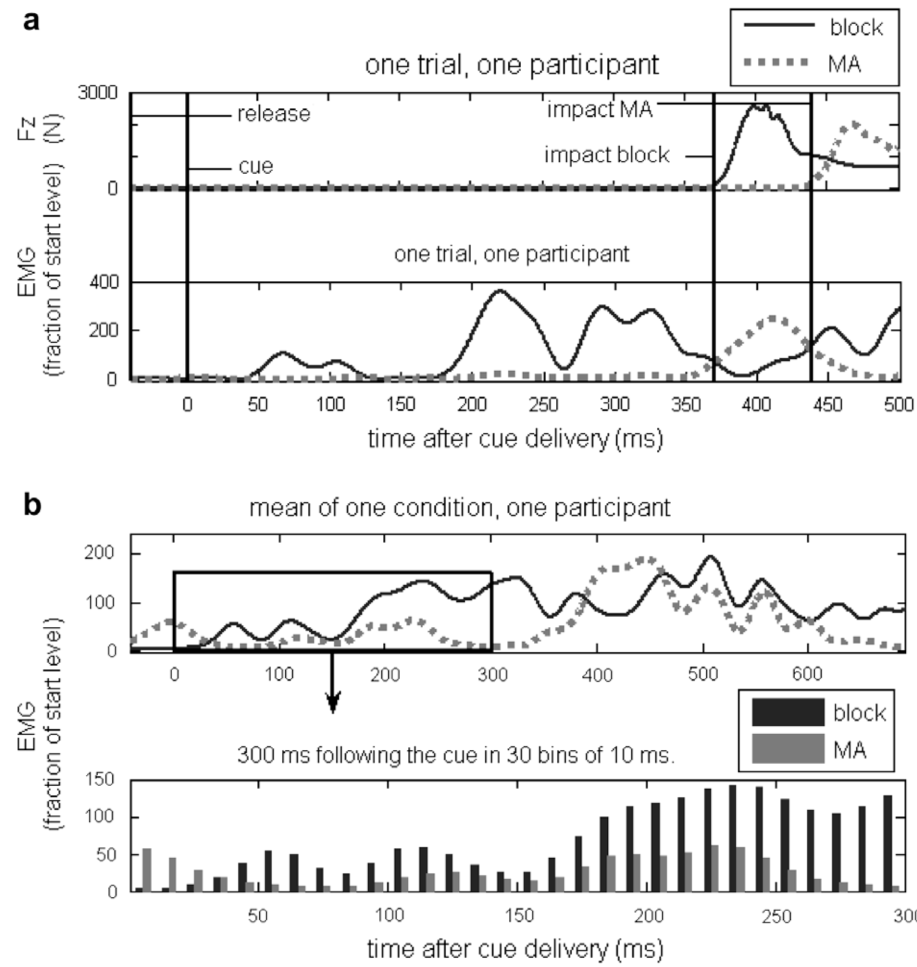

Fig. 2. Graph *a* shows an example of one participant for the 40 ms delay condition, during one trial of the MA and one trial of the block technique. The upper part of the graph shows the vertical force (Fz) and the lower part shows the normalized EMG amplitude of one exemplary muscle, the left deltoideus pars posterior (DP-left). All EMG data were normalized with respect to the mean level of activity during the starting position. Graph *b* shows the method of EMG data processing on two EMG records of DP-left. The mean of the MA and of block technique in the 40 ms delay condition are shown for one participant. The lower graph shows these records divided into 30 bins of 10 ms following the cue. Note that the EMG amplitudes of the MA and block technique start to diverge at about 190 ms.

Table 1
Means (SD) of success rates for the three cue delays in MA and block

Cue delay (ms)	Block falls			MA falls		
	1	40	80	1	40	80
Experienced ($n = 5$)	80 (14)	87 (14)	67 (16)	96 (9)	93 (10)	71 (22)
Inexperienced ($n = 9$)	91 (11)	84 (22)	91 (15)	93 (14)	86 (15)	72 (23)

During the catch trial, when no cue was given, 3 (=60%) of the experienced and 3 (=33.3%) of the inexperienced fallers used the block technique, whereas 1 (=20%) of the experienced and 3 (=33.3%) of the inexperienced fallers used the MA technique. A fall arrest that could not be labelled as block or MA was made by 1 (=20%) of the experienced and 3 (=33.3%) of the inexperienced fallers. The groups were not significantly different in their choice for MA or for block technique ($p = .754$).

3.2. Effects of technique

Differences in EMG amplitudes between techniques could be observed in all the muscles. In general, the amplitudes during 300 ms following the cue were higher in block than in MA falls. In addition, shoulder muscles demonstrated more pronounced differences in EMG amplitudes between the techniques than the abdominal and sternocleidomastoideus muscles. The EMG amplitudes for the two techniques, averaged over all subjects, are presented in Fig. 3.

Analysis revealed technique-specific differences in EMG amplitudes, as indicated by significant interactions between technique and bin in all the muscles, ($F(29,348) = 1.547$–11.598, all p values $<.038$). For six muscles (all except OA-left and SC-right) post hoc contrasts revealed a significant point of divergence, indicating that EMG amplitudes started to diverge between techniques and remained significantly different for at least four bins. For TR, DP, and

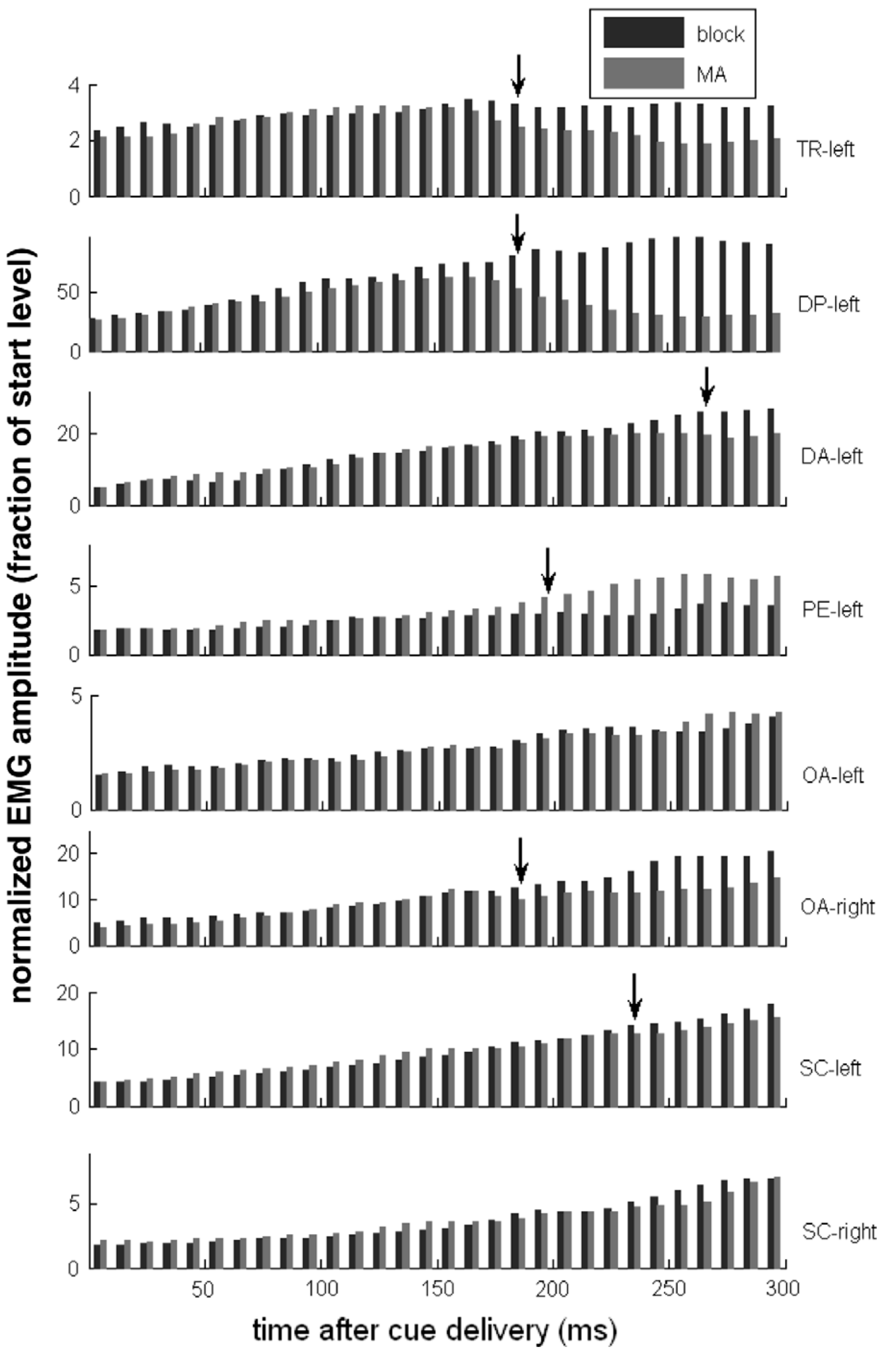

Fig. 3. Mean normalized EMG amplitudes for MA and block falls in bins of 10 ms, averaged over all participants. All EMG data were normalized with respect to the mean level of activity during the starting position. Arrows indicate the points of divergence between the EMG patterns of both techniques. For OA-left and SC-right no point of divergence could be detected.

OA-right the point of divergence was observed in bin 19 (180-190 ms, $p = .043$, $\eta_p^2 = .300$; $p = .012$, $\eta_p^2 = .423$; and $p = .028$, $\eta_p^2 = .341$, respectively). For PE, EMG amplitudes started to diverge in bin 20 (190–200 ms, $p = .038$, $\eta_p^2 = .313$), for SC-left in bin 24 (230–240 ms, $p = .038$, $\eta_p^2 = .312$), and for DA in bin 27 (260–270 ms, $p = .041$, $\eta_p^2 = .304$).

To illustrate the distinction between block and MA techniques more clearly, the differences in EMG amplitudes between the two techniques are plotted in Fig. 4 (block minus MA). This figure shows also the standard error of the difference between the EMG amplitudes of block and MA techniques to give an impression of the between-subjects variability. Following the points of divergence, technique-specific activation levels were higher in block falls than in MA falls for all the muscles, except for PE. In this muscle, the technique-specific activation was higher in the MA technique. Following the cue, EMG amplitudes in TR, DP, and OA-right during MA falls were 79%, 61% and 81% of the amplitudes during block falls. In PE,

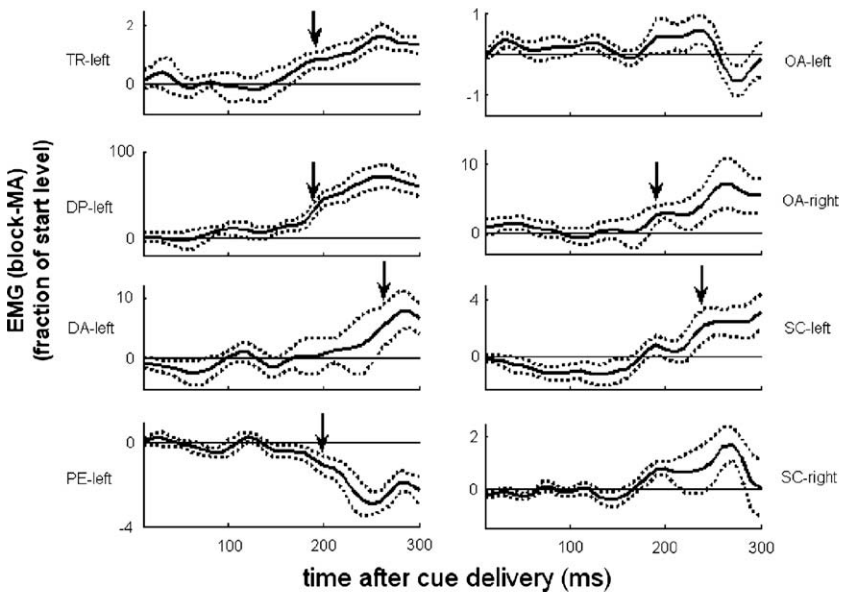

Fig. 4. Difference between mean EMG amplitudes of block and MA techniques, averaged over all participants, for the eight muscles recorded. Plus and minus one standard error of the difference is shown with dotted lines. Positive values indicate that the amplitudes of block techniques are higher than of MA techniques. All EMG data were normalized with respect to the mean level of activity during the starting position. For the six muscles that showed a point of divergence, this point is indicated with an arrow.

EMG amplitudes during MA falls were 130% of the amplitudes during block falls.

3.3. Effects of delay

To investigate whether it is possible to change the fall strategy, even if one decides to make such a change after the onset of a fall, several delays were introduced between fall initiation (release) and cue. First, an analysis of the EMGs synchronised to the instant of release of the grip was performed. By means of this analysis of 15 bins (150 ms) following release of the grip, it was investigated whether the subjects indeed postponed the start of a voluntary fall arrest strategy until the cue. Because in this time any cue-related activity was not to be expected, this analysis would also demonstrate the effect of the fall on EMG amplitudes. In all the muscles a gradual increase was obvious.

Fig. 5 presents the EMG amplitudes in the three delay conditions from release of the grip until 300 ms after the cue for one exemplary muscle. The gradual increase was confirmed by significant main effects of bin in the analyses of all the muscles ($F(14,168) = 4.426$–19.815, all p values <0.001) except for TR ($F(14,168) = 1.069$, $p = 0.389$, $\eta_p^2 = 0.082$) and SC-left ($F(14,168) = 1.045$, $p = 0.411$, $\eta_p^2 = 0.080$). The analyses failed to show significant effects of technique on EMG amplitudes in any muscle ($F(1,12) = 0.002$–3.719, all p values >0.078), except for SC-left ($F(1,12) = 5.789$, $p = 0.033$, $\eta_p^2 = 0.325$). In addition there were no significant effects of delay ($F(2,24) = 0.103$–1.421, all p values >0.261 for all the muscles).

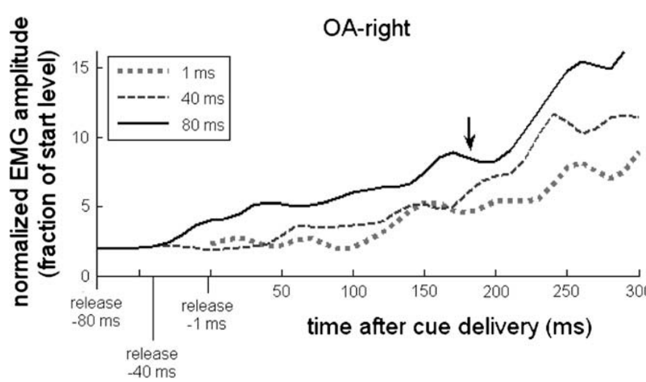

Fig. 5. Mean EMG amplitudes of one exemplary muscle (OA-right during block falls) for the three delay conditions, from release of the grip until 300 ms after the cue. All EMG data were normalized with respect to the mean level of activity during the starting position. The point of divergence is indicated with an arrow. For all delay conditions a gradual increase from the instant of release (i.e. 1, 40, and 80 ms before the cue) occurs, resulting in a difference in background activity at the point of divergence.

In the second place it was investigated whether EMG amplitudes were differently influenced by the cue delays. In the analysis of EMG amplitudes during 300 ms following the cue, there was a significant main effect of delay on EMG amplitudes in all the muscles ($F(2,24) = 5.556$–25.735, all p values $<.01$). In all the muscles, EMG amplitudes increased with increasing cue delay. In the 80 ms delay condition, mean amplitudes were on average 39% (SD 14%) larger than in the 1 ms delay condition. Post-hoc contrasts revealed that in the 80 ms delay condition all the muscles showed significantly larger overall EMG amplitudes than in the 1 ms delay condition (all p values

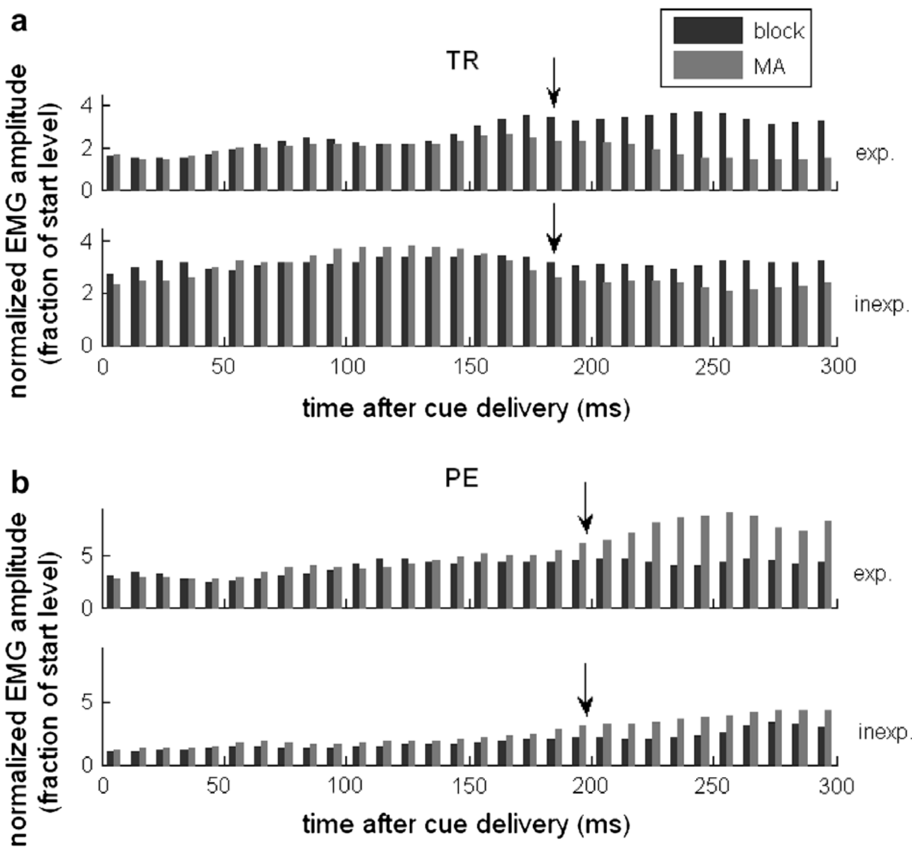

Fig. 6. EMG amplitudes, averaged over the three delay conditions, for the experienced and inexperienced group. All EMG data were normalized with respect to the mean level of activity during the starting position. In graph *a* these records are shown for the trapezius and in graph *b* for the pectoralis. Arrows indicate the points of divergence.

<.007) and the 40 ms delay condition (except for TR, all p values <.033). In addition, for TR, OA-right and SC-left significantly larger amplitudes were observed in the 40 ms compared to the 1 ms delay condition (p values <.038). To investigate if responses were more vigorous with increasing cue delay, the interaction effects between delay, technique and bin were analyzed. For none of the muscles this interaction effect was significant for 4 bins in a row.

3.4. Effects of experience

The influence of experience on the EMG amplitudes of both the block and MA falls was evaluated by comparisons of the experienced with the inexperienced group in the analysis of the 30 bins following the cue. In the six muscles with a point of divergence, which were TR, DP, DA, PE, OA-right and SC-left, the influence of experience on the differences between the block and MA techniques could be identified by interaction effects between group and technique. These interaction effects were significant in TR ($F(1,12) = 4.927$, $p = .046$, $\eta_p^2 = .291$) and in PE ($F(1,12) = 6.317$, $p = .027$, $\eta_p^2 = .345$). For these muscles, MA and block EMG amplitudes for both groups are shown in Fig. 6.

With respect to TR (see Fig. 6a), in the inexperienced group the early activation (before the point of divergence) was relatively high compared to the experienced fallers. Activation remained at this high level after the point of divergence (190 ms) in case of a block fall but decreased in case of an MA fall. In the experienced group, early activation in TR was relatively low. Activation remained at this low level after the point of divergence in case of an MA fall, but increased in a block fall. With respect to PE (see Fig. 6b), there was a steeper increase of MA-specific activity in the experienced group compared to the inexperienced fallers. In addition, analysis yielded a main effect of group for PE ($F(1,12) = 9.639$, $p = .009$, $\eta_p^2 = .834$). In PE, the inexperienced fallers had only 42.9% of the overall EMG amplitudes compared to the experienced group.

4. Discussion

The aim of the present study was to examine the neuromuscular control of a fall technique during a sideways fall. An experiment was conducted in which participants received a cue as to which fall technique (block or MA) they had to apply during an ongoing fall. The results showed that participants were able to adjust the ongoing falling movement, as they were successful in performing the requested fall techniques in 85% of the falls. Inexperienced fallers, after a 30-min training session in MA fall techniques, were as successful as experienced fallers in this task. There was no difference between the success rates of the two techniques, implying that the experimental set-up did not favor one of the techniques and that the techniques were equally difficult to implement.

4.1. Effects of technique

Neuromuscular control characteristics were evaluated on the basis of EMG recordings of eight selected shoulder and trunk muscles. In six muscles, namely TR, DP, DA, PE, OA-right and SC-left, technique-specific differences in EMG amplitudes were observed. Hence, the EMGs of these six muscles could discriminate between the MA and the block technique. Activity after the point of divergence was significantly higher during block than during MA techniques in all these muscles except PE, which was more active during an MA fall. In order to understand these differences in activation levels, it is necessary to consider the functions of the muscles in relation to the characteristics of the movements during the two different fall techniques. During a block fall, the left shoulder is elevated and the arm is outstretched into the direction of the fall, which is consistent with the enhanced activation levels of TR, elevating the shoulder, and DP and DA, abducting the arm. Trunk orientations at impact are more vertical in block than in MA falls (Groen et al., 2007), which is in line with higher activation levels of the OA-right as a muscle that lateroflexes the trunk to the right. The activation levels in these muscles were reduced in an MA fall. Characteristics of the MA fall are shoulder protraction and arm adduction, which is consistent with higher PE activation levels. The trunk rotation that is characteristic for MA falls could be partly explained by the current results. Activity of OA-left can produce heterolateral rotation of the trunk. Yet, EMG amplitudes of OA-left were not higher for MA than for block falls. On the other hand, PE is also known to contribute to trunk rotation (Kumar et al., 2003). This muscle indeed was more active in MA than in block falls. It might be that other muscles, such as the internal oblique abdominal muscle and paravertebral muscles, were also involved in trunk rotation in the MA technique. Finally, head stabilization is required in both techniques, which explains increased activation levels in SC muscles on both sides. It may be that more activity is required in block falls in order to prepare for the abrupt landing, in contrast to the rather gentle landing as a result of rolling in the MA fall. Although only SC-left shows a significant point of divergence, a similar tendency can also be observed in SC-right.

In the current study, the earliest points of divergence in the EMG patterns of the two techniques were found at 180-190 ms after the cue. Technique-specific differences in EMG activity were not expected within 150 ms after the cue, because this is the minimum time limit for simple reaction times by cortical pathways (Hase and Stein, 1998). Reaction times to a cue increase if more than one response is possible. The minimum time limit in such a choice reaction task increased by about 23 ms compared to a simple reaction task (Carson et al., 1995). Based on this number, choice reaction times for applying acquired fall techniques during a fall were expected to be at least about 175 ms. Hence, the presently observed reaction times were in line with the literature.

4.2. Effects of delay

The successfulness on the task performance was reduced by increasing time pressure. However, this decline was only significant in the highest time pressure condition (80 ms delay) as compared to both the 1 ms and 40 ms delay condition. These results are in agreement with the findings of Feldman and Robinovitch (2004), who tested the ability to avoid hip impact by rotating backward or forward on instruction, during a fall from standing height. They presented the cues with delays ranging from 300 ms before release to 300 ms after release, and found that earlier cue delivery during the fall (indicating the required direction of rotation) led to better performance of the required rotation. They identified a critical window of 200 ms within which rotation should be initiated in order to be effective. In the present study, fall durations were 405 ms on average, and reaction times were 180–190 ms. Hence, in the 80 ms delay condition only 145–155 ms remained as available movement time. This time is probably at the limit of movement times, necessary to perform the fall techniques adequately, as was indicated by the decreasing success rates in this condition. Because Feldman and Robinovitch (2004) reported only the cue delay without the total fall duration, the minimum reaction and movement time, required for adequate performance of backward and forward rotation could not be estimated from their data.

Absence of significant effects of delay and technique in the analyses of EMG amplitudes during 150 ms following release of the grip showed that there was no effect of the cue in this time. This indicated that participants postponed the start of a voluntary fall strategy until the cue. However, the start of any muscle activation was not postponed. The significant main effects of bin are indicative of increasing muscle activation with increasing time after release of the grip, independent of the cue. It might be that a gradual increase of muscle activity was present as a result of anticipatory activity to the fall arrest itself. The results of the catch trials supported this suggestion of an anticipatory fall arrest activity, as all participants employed some type of fall arrest strategy. This fall arrest, independent of the cue, might have been influenced by perception of the landing surface. In the present study, impacting the judo mat with a drop fall on the side would be at least uncomfortable. As in real-life falls usually occur on hard surfaces, the current results may indicate that the landing surface in the present set-up closely approached real-life situations.

In the analyses of the EMGs during 300 ms following the cue, significant effects of delay on amplitude were present in all the muscles. This suggested that the EMG amplitudes increased as a consequence of shortening of the available time to perform the fall technique, which may have resulted in a more vigorous response. However, when the delay of the cue increased, the cue was delivered at a later instant during the fall. As shown by the analyses of EMG amplitudes during 150 ms following release of the grip, the activity as a result of the fall itself was increased when fall duration increased. It follows that at the time of the point of divergence there was a higher background activity level in the 80 ms delay condition than in the other conditions. In other words, the gradual, fall-related increase of muscle activity was interfering with the activity resulting from a voluntary fall strategy. Hence it cannot be excluded that the increasing amplitudes with increasing cue delay could be attributed to the increasing activity as a result of the fall itself. Significant interaction effects between delay, technique and bin, that could confirm more vigorous responses in increased cue delays, were not present in this study. It might be that with a larger number of subjects these interaction effects would exist.

4.3. Effects of experience

The similarity of the success rates over the groups (experienced and inexperienced fallers) suggests that only a brief training would suffice to perform an adequate fall technique. In line with previous studies (Zehr et al., 1997; Yiou and DO, 2001), the present study showed that detailed analyses are needed to reveal differences between experts and novices in sports. Analysis of EMG amplitudes revealed that the amplitudes of TR and PE significantly differed between the groups. The experienced fallers increased MA-specific PE activity more than the inexperienced fallers (see Fig. 6b). This may have resulted in a more pronounced protraction of the shoulder, adduction of the arm and rotation of the trunk in the experienced fallers. Further analysis of kinematic data is needed to confirm this. In addition, higher early PE activation suggested that the experienced fallers prepared an MA fall, whereas early activity in TR tended to be higher in the inexperienced fallers, possibly indicating a preparation for the block technique. As a result of years of MA training, experienced fallers might have changed this automated preparation to an impending fall with the block technique, into a preparation for trunk rotation, initiated with shoulder protraction. A decrease in TR activation could be part of this altered preparation pattern as well. Previous studies showed that reduction of hip impact force by application of the MA fall was more pronounced in judokas than in non-judokas (Weerdesteyn et al., 2007). This larger reduction in experienced fallers may have been caused by the altered preparation and/or more pronounced technique-specific PE activation in this group. This might have resulted in a better trunk curvature, allowing a more optimal distribution of impact forces along the contact path. Further analysis of trunk kinematics and impact forces could provide more insight into this issue.

4.4. Limitations of the study

A limitation of the study was that the falls were self-initiated, whereas falls in real life are not. To imitate real-life falls more closely, falls in the present experiment were initiated on command to release the grip. In this way the subjects, just like in real-life falls, could not choose the instant of fall initiation freely. The cue delay was mimicking the time, during a real-life fall, available to detect loss of balance and to decide to apply a fall technique. Falls in real-life may be accompanied by automated reactions, such as startle reactions, as a result of the detected loss of balance. Due to the voluntary nature of the falls, startle reactions were absent in the present experiment, as evidenced by the absence of short-latency startle reactions in SC, indicative of startling (Carlsen et al., 2003). Since startles are known to speed up voluntary responses, it might be that in real-life falls the reaction times of 180–190 ms, as observed in the present study, could even be advanced.

Secondly, this experiment was performed with young women. The question remains whether the current results of voluntary fall techniques can be extrapolated to the elderly. Reaction times of elderly people to consciously initiate a fall technique are probably longer than those observed in young participants. Previous studies showed increases in latencies of 31–117 ms for voluntary movements in the elderly (Chen et al., 1994; Luchies et al., 1994; Robinovitch et al., 2005; Tirosh and Sparrow, 2005). Moreover, in the elderly movement times increase as well (Robinovitch et al., 2005) as a result of changes in muscle properties and muscle control (Pijnappels et al., 2005; Thelen et al., 2000). Further research has to be done to investigate how much additional time elderly people would need to apply a fall technique properly.

Finally, the sample size in the current study was rather small and unequally divided over the experienced and inexperienced fallers. The unequal distribution of the participants over the groups was due to the hesitation of experienced judokas to participate in a fall study. It might be that, with larger numbers of participants, outcomes would be more pronounced. However, even with the small number of experienced fallers, significant differences were found between the groups.

4.5. Implications of the study

MA techniques could be successfully implemented within fall durations of 405 ms. The duration of a real-life fall from standing height has been reported to be 715 ± 160 ms (Robinovitch et al., 2005). Hence, it should be possible to apply these techniques during a real-life fall from standing height as well. The results showed that there is a critical period before impact, within which a fall technique should be initiated, to be performed correctly.

In line with the conclusions of a previous study (Weerdesteyn et al., 2007), the present study showed that the MA fall technique is easy to learn. Previous studies showed that the MA fall technique markedly reduced hip impact forces. For this reason, the MA fall technique should be preferred over the block technique in reducing fall related injuries. With these findings, incorporation of fall techniques and in particular of MA techniques in fall prevention programs is supported. Differences in early activity of PE, as found in the present study, suggested that experienced fallers anticipated a possible fall with a preparation for trunk rotation, in contrast to the inexperienced fallers. Moreover, differences indicated a more pronounced use of PE during an MA fall in experienced fallers. The experience-related differences in activation profiles indicate that in MA falls training, the element of shoulder protraction deserves specific attention. The amount of training needed to optimally benefit from training of MA fall techniques (in terms of impact reduction) and their application in real-life falls should be further investigated, to be able to weigh the costs of extensive training against the benefits for additional reduction of injury risk.

5. Conclusions

The results of this study showed that it was possible to apply a fall strategy that was cued during a fall. The decreasing success rates with increasing cue delay supported the hypothesis that there is a limit in the cue delay still leaving enough time to perform the fall technique. For the application of a voluntary fall technique during a sideways fall from kneeling height this minimum movement time, necessary to perform the fall technique adequately, was about 145–155 ms.

The EMGs showed reactions to the cue at onset latencies of about 180–190 ms, which was the minimum reaction time that could be expected for a choice reaction task, as used in the present experiment. The EMG amplitudes showed technique-specific differences that could mainly be explained by the different functions of the muscles during the techniques.

The effects of time pressure on the performance of the fall technique might be a more vigorous response. In the present study the potential presence of this effect of time pressure was obscured by an increase of EMG amplitudes during the fall, independent of the cue. The observation that only subtle differences could be detected in EMG activity between experienced and inexperienced people supported previous findings that MA fall techniques are easy to learn.

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