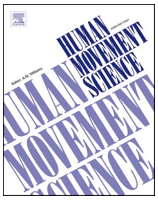
Human Movement Science 90 (2023) 103115

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov



How to improve movement execution in sidestep cutting? Involve me and I will learn

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ARTICLE INFO

Keywords:
Autonomy
Movement analysis
Motor learning
Retention
Video feedback
Sidestep cutting

ABSTRACT

Providing choices, i.e., autonomy, to athletes during practice increases intrinsic motivation and positively influences the motor learning process. The effects of autonomy on the timing of feedback (self-controlled timing of feedback) when optimizing the movement execution of sidestep cutting (SSC), a task that is highly related with ACL injury risk, are unknown. The aim of this study was to investigate the effect of self-controlled timing of video and EF-feedback on movement execution of SSC in team sport athletes. Thirty healthy ball team sport athletes (22.9 ± 1.7 years, 185.5 ± 7.2 cm, 79.3 ± 9.2 kg) were recruited from local sports clubs. Participants were alternately assigned to the self-control (SC) or the yoked (YK) group based on arrival and performed five anticipated and five unanticipated 45° SSC trials as pre-, immediate-post and one-week retention test. Movement execution was measured with the Cutting Movement Assessment Score (CMAS). Training consisted of three randomized 45° SSC conditions: one anticipated and two unanticipated conditions. All participants received expert video instructions and were instructed to 'try to do your best in copying the movement of the expert'. The SC group was allowed to request feedback whenever they wanted during training. The feedback consisted of 1) CMAS score, 2) posterior and sagittal videos of the last trial and 3) an external focus verbal cue on how to improve their execution. The participants were told to lower their score and they knew the lower the score, the better. The YK group received feedback after the same trial on which their matched participant in the SC group had requested feedback. Data of twenty-two participants (50% in SC group) was analyzed. Pre-test and training CMAS scores between groups were equal ($p > 0.05$). In the anticipated condition, the SC group (1.7 ± 0.9) had better CMAS scores than the YK group (2.4 ± 1.1) at the retention test ($p < 0.001$). Additionally, in the anticipated condition, the SC group showed improved movement execution during immediate-post (2.0 ± 1.1) compared to pre-test (3.0 ± 1.0), which was maintained during retention ($p < 0.001$). The YK

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https://doi.org/10.1016/j.humov.2023.103115
Received 3 June 2022; Received in revised form 29 March 2023; Accepted 1 June 2023

group also improved in the anticipated condition during immediate-post (1.8 ± 1.1) compared to pre-test (2.6 ± 1.0) ($p < 0.001$) but showed decreased movement execution during retention compared to immediate-post test ($p = 0.001$). In conclusion, self-controlled timing of feedback resulted in better learning and greater improvements in movement execution compared to the control group in the anticipated condition. Self-controlled timing of feedback seems beneficial in optimizing movement execution in SSC and is advised to be implemented in ACL injury prevention programs.

1. Introduction

An anterior cruciate ligament (ACL) injury had profound short and long term physical (Kuenze, Collins, Pfeiffer, & Lisee, 2021) and psychological consequences (Padaki et al., 2018). Therefore, prevention of such an injury is crucial. Current ACL injury prevention programs do not lead to a decrease of the ACL injury incidence (Weitz, Sillanpää, & Mattila, 2020;Kuenze et al., 2021). This may point out that athletes are not transferring their learned skills to real training or game situations, which involve complex challenges (i.e., teammates, opponents, pressure, fatigue etc.).

Most ACL injuries are non-contact injuries while approaching an opponent using a single leg deceleration or sidestep cutting (SSC) maneuver (Lucarno et al., 2021). Video analyses have shown frequent hip abduction, knee abduction and external rotation of the knee combined with a flat foot or heel strike pattern while rupturing ACL (Della Villa et al., 2020; Lucarno et al., 2021). To reduce the risk of ACL injuries, a number of strategies during SSC have a positive influence on movement execution: minimizing knee abduction moments, landing on the toes, and rotation plus lateral flexion of the trunk towards intended direction (Dempsey et al., 2007; Dos'Santos et al., 2019; Fox, 2018; Nijmeijer, Elferink-Gemser, Otten, & Benjaminse, 2022). One way to quantify the SSC movement execution is with the Cutting Movement Assessment Score (CMAS) (Jones, Donelon, & Thomas, 2017). As many cutting maneuvers on the field are unplanned and athletes have to quickly anticipate and respond to several stimuli, it is essential to expose athletes to challenging, unpredictable environments during preventation training (Benjaminse & Verhagen, 2021). To obtain a safer cutting execution with reduced knee loads, a relatively permanent change in movement strategy is required (retention) (Kantak & Winstein, 2012; Lohse, Wadden, Boyd, & Hodges, 2014), which also remains in new circumstances (transfer) (Schmidt & Lee, 2011). Increased understanding of learning a sport-specific task, including retention and transfer, is an important contribution to enhance current ACL injury prevention programs.

Autonomy is a key element in the OPTIMAL theory of motor learning. This theory proposes that autonomy, enhanced expectancies and external focus of attention (EF) enhance performance and learning by strengthening the coupling of goals to actions (Wulf & Lewthwaite, 2016). Autonomy means that athletes are given a certain amount of control over particular aspects of their training, which makes them feel that this influences their own actions (Almagro, Sáenz-López, & Moreno, 2010). This involvement is thought to increase intrinsic motivation and therefore, positively influences the motor learning process (Chiviacowsky, Wulf, & Lewthwaite, 2012). Furthermore, it leads to feelings of competence of the athlete (Chiviacowsky et al., 2012), contributing to long term changes in behavior of the motor skill (Sanli, Patterson, Bray, & Lee, 2013).

Autonomy on the timing of feedback may be successful in enhancing motor learning because athletes will receive feedback when they believe it is useful (Grand et al., 2015; Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017). Moreover, it provides athletes with relevant information and is associated with more effective (Lim et al., 2015) and task-related processing activities, such as error-estimation (Carter & Ste-Marie, 2017). Task-relevant choices with informational value seem to lead to greater improvements compared to task-irrelevant choices (Carter & Ste-Marie, 2017; Ikudome, Kou, Ogasa, Mori, & Nakamoto, 2019). Improved movement execution of jump landing was found in participants who received a training program with EF instructions compared to those who received internal focus of attention (IF) instructions (Dalvandpour et al., 2021). Also, self-controlled timing of feedback combined with EF instructions and visual instructions enhanced jump landing execution during a retention test compared to self-controlled timing of feedback combined with IF instructions (Welling, Benjaminse, Gokeler, & Otten, 2017). It is suggested that visual instructions directed to the movement outcome in combination with self-controlled timing of feedback increases intrinsic motivation and therefore, positively influences the motor learning process (Chiviacowsky, Wulf, de Medeiros, Kaefer, & Tani, 2008). Despite its relevance, no study so far has investigated the effects of self-controlled EF feedback on movement execution when finetuning a sport-specific task. Therefore, the aim of the present study was to investigate the effect of self-controlled timing of video and EF-feedback on the movement execution of SSC in team sport athletes. It was expected that the self-controlled group made greater progress after receiving the training compared to their yoked counterparts.

2. Method

2.1. Participants

Thirty healthy participants (22.9 ± 1.7 years, 185.5 ± 7.2 cm, 79.3 ± 9.2 kg) were recruited from local sports clubs in Groningen, The Netherlands. For inclusion, participants had to be 1) male, 2) between 18 and 30 years old and 3) experienced with or currently physically active in a recreational ball team sport. Participants were excluded if 1) they had a lower extremity injury at the time of the study or 2) if they ever had knee surgery. After inclusion, participants were alternately assigned to the self-control (SC) or the yoked

(YK) group based on arrival, creating matched SC-YK pairs. With a partial eta squared of 0.10 (medium effect) and an alpha of 0.05, a power of 0.80 was reached with 28 participants. G*Power for Windows, version 3.1.9, was used to calculate the required sample size (Faul, Erdfelder, Lang, & Buchner, 2007).

2.2. Procedures

Informed written consent of participants was obtained prior to inclusion. Ethical approval was obtained from the Medical Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (ID number: METc 2018.249). All participants wore shorts and their own athletic shoes during testing.

After a general instruction, participants completed a short warming-up. On the first day, participants performed the pre-test, training and immediate-post test. A retention test was performed one week later. Prior to every new test or condition, participants were given ample time to familiarize themselves with the set-up.

2.3. Task

The task used in this study was a SSC task. Participants used a five meter approach run followed by a one foot landing on the force plate and a 45° change in direction followed by running through a timing gate five meter away from the force plate (see Fig. 1). A SSC trial was defined as successful if the cut angle of 45° was in the non-dominant leg direction with the dominant leg (i.e., the leg they preferred pushing off and landing with (Benjaminse, Welling, Otten, & Gokeler, 2018; Nijmeijer et al., 2022)) on the force plate. In addition, participants were verbally encouraged to run and cut at submaximal speed and coached them when they deviated from this.

2.3.1. Pre-test

After familiarization, participants performed pre-test trials to collect baseline values of the task. Participants performed five trials for each condition (anticipated and unanticipated). These conditions were completed in a counterbalanced order across all participants to avoid possible order effects. For the anticipated condition, the participant knew beforehand to which direction the cut needed to be made. The Speedlight Timing System (Speedlight Timing Systems, Swift Performance LLC, Northbrook, USA) was used for the unanticipated condition. One of the lights indicated the direction (45° SSC in non-dominant leg direction, straight forward, 45° SSC in dominant leg direction) to run towards. One of the lights started to fire randomly at the very moment the participant passed the start gate. The start gate was located 3 m away from the force plate. Only trials performed in 45° in the non-dominant leg direction were used for the analysis. To put all participants at ease and give feelings of control throughout all sessions, comments such as ‘feel free to ask anything that is unclear’, ‘you can start with the trial whenever you feel ready’, ‘you are doing a great job’ and ‘you can always take some rest if you want’ were given.

2.3.2. Training blocks

Both groups performed four training blocks of five trials, similar to a previous study of our group (Welling et al. (2017)). Three

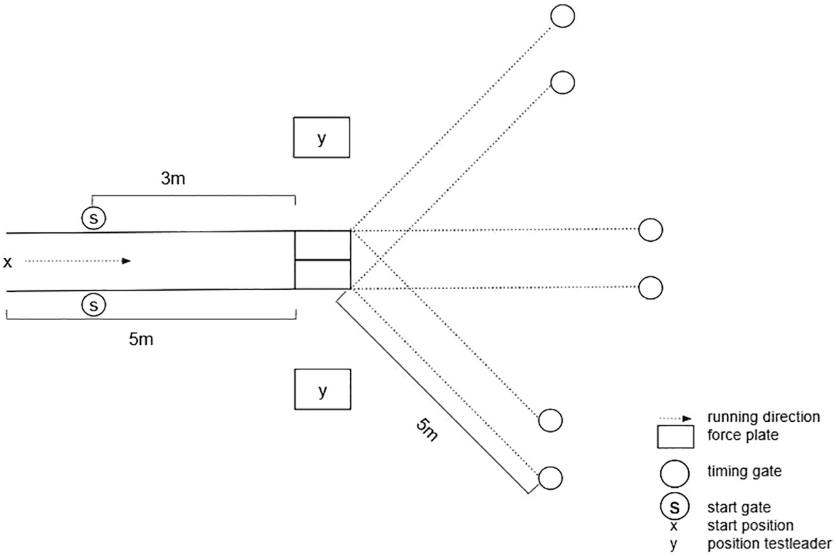

Fig. 1. Participants used about a five meter approach run followed by a 1-foot landing on a floor-embedded force plate and a 45° change in direction through a set of timing gates five meter away from the force plate. For the unanticipated condition, when the participant passed the start gate, randomly one of the timing gates started to flash. This was electronically controlled. x = start position participant, y = position testleader (depending on the leg dominance of the participant either on the right or left side).

different variations of a SSC were chosen: 1) an anticipated SSC as described for the pre-test, 2) an unanticipated SSC with catching and throwing a ball while cutting and 3) an unanticipated SSC after passing a ball to the testleader with their dominant leg. Three different randomized sequences were used to counterbalance any influence of the amount of trials for each SSC variation or the order of the variations. Each sequence consisted of 7 trials of one variant and 6 trials of each of the other variants. The testleader stood in a 1 m by 1 m square indicated by tape, on the same side as the participant ran to (see Fig. 1).

To optimally activate neural structures involved in the planning and execution of skills, variable practice is preferred above no variation (Lage et al., 2015). Moreover, random practice is shown to be more favourable compared to blocked practice (Mohammadi Orangi et al., 2021). Therefore, expectancies were enhanced by providing the three variations, adding a ball to make it more sport-specific and a randomized order of variations to perform. The participants in the YK group followed the same randomized order as their partner in the SC group. Before every trial, the participant was told which variation to perform. A trial was valid when the foot was fully placed on the force plate and the ball was passed or thrown back properly to the testleader. Again, the participant was informed that trials could be repeated.

2.3.3. *Immediate-post test and retention test*

The immediate-post and retention test followed after finishing the training blocks and one week later, respectively. For both tests, participants followed the same protocol as the pre-test. Moreover, they started with the same condition in the immediate-post and retention test as they had started with in the pre-test. All participants were given the same general comments regarding feelings of control as they had received during the pre-test. No group specific instruction or feedback was given during these tests.

2.4. *Instruction and feedback*

Before each training block, an expert video of a SSC was shown from both sagittal (i.e., side of the dominant leg) and posterior view to both groups, at ca. 70% of real speed. The expert was a competitive soccer player. Sex, body height and body mass were matched with the participants. The expert videos of SSCs were selected based on previous research, i.e., with minimal knee joint loading (Benjaminse et al., 2018; Benjaminse, Otten, Gokeler, Diercks, & Lemmink, 2017; Welling, Benjaminse, Gokeler, & Otten, 2016). Those videos were created before the start of data collection and made available for providing instruction to all participants. Two specific implicit instructions were given along with the video; ‘pay attention to the entire movement the expert makes just prior to and during cutting’ and ‘try to do your best in copying the movement of the expert’ (Benjaminse et al., 2017). After showing the expert videos to the participant, only participants in the SC group were told that they were free to ask for feedback whenever they wanted during the training blocks. All participants were told that feedback is crucial to improve movement execution (Parsons & Alexander, 2012) and were stimulated to improve their movement execution. The SSC execution was assessed by means of the Cutting Movement Assessment Score (CMAS) (Jones et al., 2017). Their goal was to lower the score to the best of their ability. Moreover, participants were told that a lower score meant a better movement execution. No further details about the scores were mentioned (Welling et al., 2016). Both groups were informed that, when feedback was provided, the feedback would consist of three items. First, the CMAS score of that respective trial was given (Jones et al., 2017). Subsequently, the participant received video feedback on a screen showing their trial belonging to that score, from both a sagittal and posterior plane view in a randomized order. Third, based on their score, the participants received one EF feedback cue about how to improve their movement execution (Appendix A) (Wulf, 2013). During the training blocks, the YK group was not allowed to ask for feedback. As each participant in the YK group was yoked to one participant in the SC group, the yoked counterparts received feedback after the same trial of which their partner in the SC group had requested feedback. In this way, the absolute numbers of feedback trials and timing of feedback during practice were identical for both groups. The SC group was randomly reminded about the fact that they could ask for feedback whenever favoured.

2.5. *Apparatus*

Two 50 Hz Basler video cameras (cameras with a 25-mm and 9-mm C-mount lens Basler Inc., Exton, PA, USA) recorded the sagittal and posterior plane view of the participants performing the tasks. Videos of the performed trial were shown on a PC screen. Two Q4n cameras (2304 × 1296, 30fps) with a 16.6-mm lens recorded frontal plane- and 45 angle views of the participant performing the SSC. These recordings were used to determine CMAS scores during the training blocks.

2.6. *Data acquisition and statistical analysis*

The CMAS (range 0–11) assesses penultimate foot contact braking strategy, and hip, knee, foot and trunk postures and motions during the final step (45° change in direction) (Appendix B) (Jones et al., 2017). Athletes receive a point from the testleader if they display any of the items of the CMAS criteria, higher scores indicate a poorer execution (Dos’Santos et al., 2019; Jones et al., 2017). The testleaders were trained by AB in the weeks prior to conducting the project. Several pilot sessions to improve inter- and intrarater reliability have been conducted. Excellent inter- and intra-rater reliability of this score has been found previously (ICC = 0.91–0.94) (Dos’Santos et al., 2019; Jones et al., 2017). Furthermore, a strong positive relationship between CMAS and peak knee abduction moments was found ($\rho = 0.796$) (Dos’Santos et al., 2019).

While scoring the videos, we unexpectedly found that eight participants performed the task incorrectly in one or more sessions. Therefore, we decided to remove these participants from the data set and ended up with 22 participants (11 in SC and 11 in YK group). Of the remaining participants, 55 scores (out of 660) of the testing phase were missing because of missing video data or incorrect task execution. These scores were replaced by taking the mean of the condition and session for the specific participant. A one-way ANOVA was used to compare the pre-test values between the SC and YK group. Subsequently, differences between and within groups (pre-, immediate-post and retention test) were determined with a repeated measures MANOVA for the anticipated and unanticipated condition. A repeated measures ANOVA was used to test the differences between the four training blocks and two groups. Statistical analyses were performed using SPSS (version 27.0.0; IBM Corp, Armonk, NY) with alpha set at $\alpha \leq 0.05$ a priori. Partial eta squared (η_p^2) values were reported as a measure for effect size for the significant main effects and interactions (< 0.06 = small, 0.06–0.14 = medium, > 0.14 = large) (Cohen, 2013). Post-hoc Bonferroni corrections were performed when necessary. Cohen's d values were used as effect size for the post-hoc comparisons for which partial eta squared was not appropriate (0.2–0.5 = small, 0.5–0.8 = medium, $>$ 0.8 = large) (Cohen, 2013). Sphericity was not assumed for the anticipated condition in the testing phase ($p = 0.019$), therefore a Greenhouse-Geisser correction was applied.

3. Results

Table 1 shows the results of the repeated measures MANOVAs. No significant differences were found between the SC and YK group at pre-test for either the anticipated (3.0 ± 1.1 vs 2.6 ± 1.0) or unanticipated (3.5 ± 0.8 vs 3.5 ± 1.3) condition ($p > 0.05$). Taking all tests and participants together, significant better scores were found in the anticipated (2.2 ± 1.1) compared to the unanticipated condition (3.2 ± 1.1) ($p < 0.001$).

3.1. Testing phase

3.1.1. Interaction effects

A significant interaction was found between time and group for the anticipated condition ($F(1.87,216) = 10.76$, $p < 0.001$, $\eta_p^2 = 0.09$). Further analysis revealed significant differences between the SC (1.7 ± 0.9) and YK group (2.4 ± 1.1) in the retention test ($p < 0.001$, $d = 0.71$). Furthermore, the SC group showed better scores in the retention test (1.7 ± 0.9) compared to the pre-test (3.0 ± 1.1) ($p < 0.001$, $d = 0.88$) whereas the YK group showed worse scores in the retention (2.4 ± 1.1) compared to the immediate-post test (1.8 ± 1.1) ($p = 0.001$, $d = 0.53$). The SC and YK groups improved their scores from the pre-test (3.0 ± 1.0 and 2.6 ± 1.0) to the immediate-post test (1.9 ± 1.1 and 1.8 ± 1.1) ($p < 0.001$, $d = 0.69$ and $d = 0.81$). No significant interaction effects between time and group were found for the unanticipated condition ($p > 0.05$).

Table 1
Results of repeated measures MANOVAs ($n = 22$).

	Factor	F-value	P-value	η_p^2	Post-hoc
Anticipated condition (testing phase)	Time	30.54	<0.001***	0.220[a]	Pre > imm ($p < 0.001$***, $d = 0.731$[b]) Pre > ret ($p < 0.001$***, $d = 0.471$[c])
	Group	0.14	0.714		
	Time * group	10.76	<0.001***	0.091[b]	Ret: SC < YK ($p < 0.001$***, $d = 0.706$[b]) SC: pre > ret ($p < 0.001$***, $d = 0.876$[a]) & pre > imm ($p < 0.001$***, $d = 0.692$[b]) YK: ret > imm ($p = 0.001$**, $d = 0.533$[b]) & pre > imm ($p < 0.001$***, $d = 0.812$[a])
Unanticipated condition (testing phase)	Time	10.64	<0.001***	0.090[b]	Pre > imm ($p = 0.003$**, $d = 0.328$[#]) Pre > ret ($p < 0.001$***, $d = 0.448$[#])
	Group	1.24	0.268		
	Time * group	2.70	0.070		
Anticipated and unanticipated condition (training phase)	Block	12.98	<0.001***	0.394[a]	4 > 2 ($p = 0.003$**, $d = 0.892$[a]) 4 > 1 ($p = 0.001$**, $d = 1.037$[a]) 3 > 2 ($p = 0.043$*, $d = 0.652$[b]) 3 > 1 ($p = 0.019$*, $d = 0.727$[b])
	Group	1.70	0.207		
	Block * group	0.13	0.941		

Pre = pre-test, imm = immediate-post test, ret. = retention test, SC = self-control group, YK = yoked group.
Note: only significant post-hoc tests are displayed, e.g., in anticipated condition immediate-post scores were significantly better compared to pre-test scores.

*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.
[a] Large effect size.
[b] Medium effect size.
[c] Small effect size.

3.1.2. Effects of time and group

Regardless of group, a significant main effect of time was found for the anticipated ($F(1.87,216) = 30.5$, $p < 0.001$, $\eta_p^2 = 0.22$) and unanticipated condition ($F(2,216) = 10.6$, $p < 0.001$, $\eta_p^2 = 0.09$). CMAS scores of the anticipated condition on the pre-test were worse (2.8 ± 1.0) compared to the immediate-post test (1.9 ± 1.1) and the retention test (2.0 ± 1.1) ($p < 0.001$, $d = 0.73$ and $d = 0.47$). Similarly, for the unanticipated condition, worse scores were found in the pre-test (3.5 ± 1.1) compared to the immediate-post (3.1 ± 1.2) ($p = 0.003$, $d = 0.33$) and the retention test (3.0 ± 1.1) ($p < 0.001$, $d = 0.45$). No significant main effects of group were found for both conditions ($p > 0.05$). Fig. 2 shows the CMAS scores distribution and significant differences between tests and groups.

3.2. Training phase

Fig. 3 displays the scores of the separate blocks for both groups. Regardless of group, a significant effect of time was found ($F(3,60) = 12.98$, $p < 0.001$, ${\eta_p}^2 = 0.39$). Post-hoc comparisons showed better scores in block 4 (1.8 ± 0.8) compared to block 1 (2.7 ± 0.9, $p = 0.001$, $d = 1.04$) and block 2 (2.6 ± 0.9, $p = 0.003$, $d = 0.89$). In addition, the scores in block 3 (2.1 ± 0.9) were significantly better compared to block 1 ($p = 0.019$, $d = 0.73$) and block 2 ($p = 0.043$, $d = 0.65$). No significant interaction effects or differences between groups over time were found ($p > 0.05$).

4. Discussion

Our study investigated the effects of autonomy on the timing of video and EF-feedback on movement execution of SSC in team sport athletes. In addition, during training we applied optimal motor learning for all participants by using implicit learning strategies and enhanced expectancies by means of variation, adding sport-specificity and feedback scores. The autonomy on the timing of feedback was the only factor that was manipulated between the groups. Our hypothesis that the SC group would show more progress compared to the YK group after the intervention was partly confirmed.

4.1. Effect of autonomy

Interestingly, the SC and YK group showed different patterns of CMAS scores over time in the anticipated condition regarding the testing phase. The YK group showed worse performance one week after the training compared to directly after the training, whereas the SC group showed similar performance during these tests. It is even more interesting to see that the SC group outperformed the YK group in the retention test for the anticipated condition when no autonomy was given and only learning effects of the training phase were tested (Fig. 2). Apparently, the learning process continued. There is evidence that consolidation processes evolve over a period of several hours as well as over sleep (Kantak & Winstein, 2012; Siengsukon & Boyd, 2009). This enhancement of offline learning refers to improvement in performance without any physical practice and is sleep-dependent (Kantak & Winstein, 2012). The learning process took time and this also explains why the better scores of the SC group in the retention test were not observed during the immediate-post test. There was a similar pattern visible for the unanticipated condition, although it was not significant. Similar beneficial effects of self-controlled timing of feedback were found on golf putting accuracy and movement pattern (Jalalvand, Bahram, Daneshfar, &

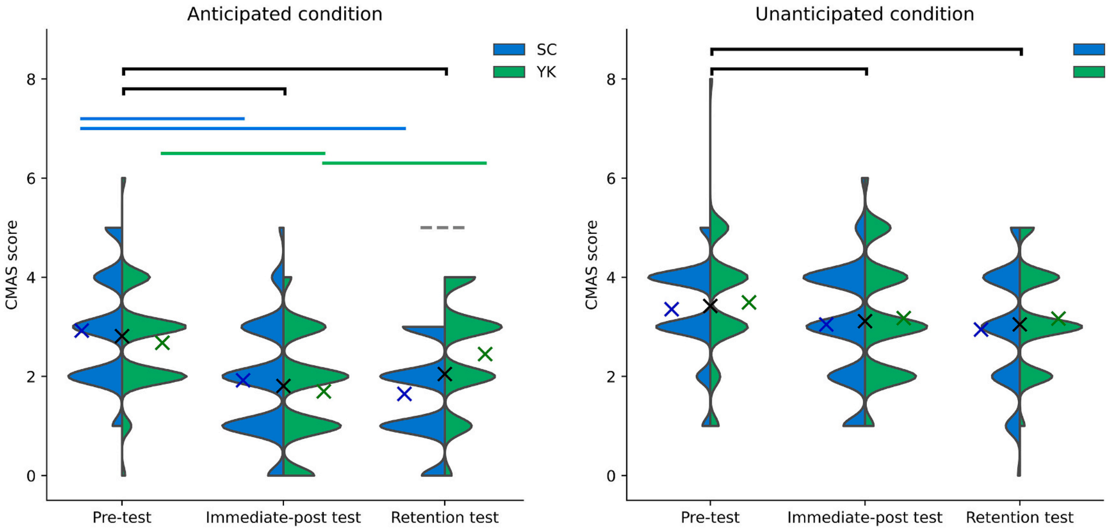

Fig. 2. Distribution of scores of the anticipated and unanticipated condition over time. The black cross indicates the mean per session regardless of group, the blue (SC group) and green (YK group) crosses indicate the mean per session. The grey dotted line indicates a significant difference between groups. The blue (SC group) and green (YK group) lines indicate significant differences between sessions. The bracket lines indicate significant differences over time regardless of group. For all significant differences; $p < 0.01$.

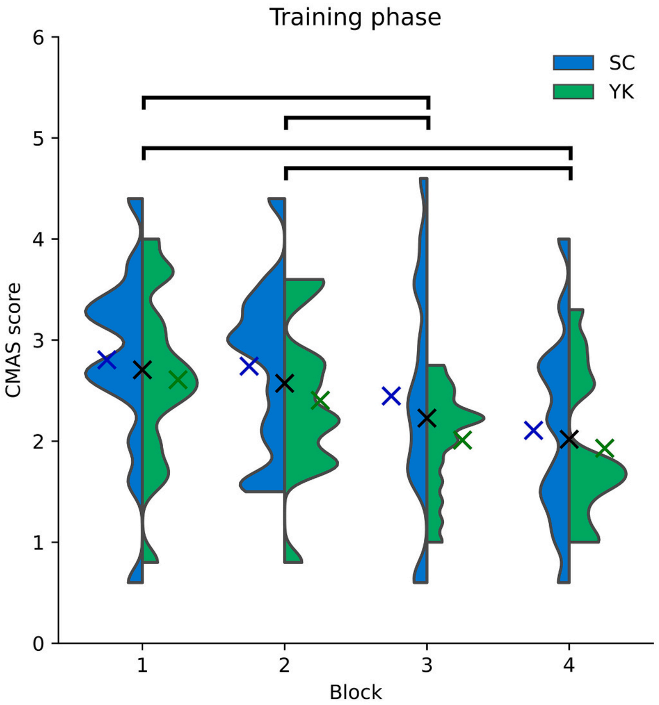

Fig. 3. Distribution of scores of the training phase per block. The black cross indicates the mean per session regardless of group, the blue (SC group) and green (YK group) crosses indicate the mean per session. The bracket lines indicate significant differences between blocks regardless of group ($p < .05$). Note: no significant differences were found within and between the SC and YK group over time.

Arsham, 2019) and a sequential motor task (Kim et al., 2019).

The SC group benefited from the possibility to ask feedback whenever they believed it was useful (Grand et al., 2015). In this way, it lies more in line with the athlete's needs or preferences than feedback imposed by others (Chiviacowsky et al., 2008; Chiviacowsky & Wulf, 2002), leading to higher motivation (Chiviacowsky et al., 2008) and self-regulation (Kim et al., 2019). Multiple studies have shown a positive relation between self-regulation and level of sport performance (e.g., Jonker, Elferink-Gemser, & Visscher, 2010; Toering et al., 2011). A recent study among talented swimmers shows that those who improve their performance most over the course of a season are characterized by higher scores on aspects of self-regulation (Post, Koning, Visscher, & Elferink-Gemser, 2022). This suggests that training and learning processes become more effective and efficient, which may also be the case in the current study. Previous research showed that autonomy on the timing of video demonstration led to more positive thoughts during practice relative to the control group who reported more negative thoughts (Lemos et al., 2017). The sense that one has control over the timing of feedback and being involved in analysing one's own performance, enhances expectations for future success (e.g., self-efficacy) (Benjaminse et al., 2018). Self-efficacy aligns attention, motivation and neuromuscular activity to the performer's goals (Lemos et al., 2017). Moreover, greater self-efficacy has been associated with increased motor learning (Chiviacowsky, 2014; Chiviacowsky et al., 2012).

The provided autonomy resulted in a higher degree of improvements in movement execution in the anticipated condition. This may suggest that giving athletes some freedom results in biomechanical changes by self-exploration and self-organizing. This can lead to more individual adaptive solutions for a task because there is a search or exploration of the task solution space. It is thought that this flexibility makes an athlete prepared to adapt to (unexpectedly) changing conditions and constraints, and to move with greater skill and fluency (Mohammadi Orangi et al., 2021). In the current study, participants did also show improvements in the unanticipated condition, but this improvement did not differ between groups. A relatively small number of trials during the training phase ($n = 20$) was used. Possibly, participants would need more practice trials to optimize self-exploration and self-organization in changing situations asking for flexibility and fast reaction to evoke also enhancements of providing autonomy on the ability for transfer of movement patterns.

4.2. *Effect of training*

Taking all participants together, the pre-test CMAS scores were already quite good. It is noteworthy that both groups showed better CMAS scores immediately after the training phase (anticipated: 1.9 ± 1.1, unanticipated 3.1 ± 1.2) and one week later (anticipated: 2.0 ± 1.1, unanticipated 3.0 ± 1.1) compared to the pre-test (anticipated: 2.8 ± 1.0, unanticipated 3.5 ± 1.1) for both conditions. This indicates that unless there was less room for improvement, a learning effect took place. Two components of the OPTIMAL model, enhanced expectancies and EF, were integrated in the training for both groups. Beneficial effects of a combination of these two components was previously shown (Pascua, Wulf, & Lewthwaite, 2015), potentially explaining the better scores seen during immediate-post and retention tests. In addition, participants were shown their own movement execution and received the belonging score. Observation gives opportunities for the participants to reflect and extract important information. With this, the participant could explore and then select the movement solutions that fit best in his own body (Benjaminse & Otten, 2011). The combination of expert and own performance videos was useful to reduce knee abduction moment in a previous study investigating SSC movement execution (Dempsey, Lloyd, Elliott, Steele, & Munro, 2009). As a SSC task is a complex movement, feedback cues may be advantageous to achieve modification of whole-body execution. Though, this feedback should be relatively simple as complex feedback hampers motor learning (Benjaminse, Welling, Otten, & Gokeler, 2015). Previous research already showed improved SSC execution after providing EF cues (Benjaminse et al., 2017). In the current study, participants were provided with short individually tailored EF feedback cues. With this, we stepped off from one-size-fits-all feedback and aimed to optimize the individual learning curve. Lastly, as random practice is more favoured compared to blocked practice (Mohammadi Orangi et al., 2021), this may have had additional benefits on the learning process as well. Therefore, it is thought that the combination of enhanced expectancies, EF feedback, CMAS score, video-instruction and feedback stimulated motor learning and explained the improvement of SSC movement execution observed in the training phase of both groups.

4.3. *Changes in movement execution in the SC group*

Inspecting the item-scores of the CMAS (Appendix C), the largest differences between pre-test and retention test were found for foot position in the frontal plane (~0.4 point, 95% reduction) and frontal trunk position relative to intended direction (~0.5 point, 75% reduction) in the SC group. These reductions mean that participants placed their foot more neutral in the frontal plane and the trunk towards the intended direction in the retention test. A neutral foot position is likely to result in forces being absorbed in the sagittal plane utilising knee and hip extensor muscles (Jones, Herrington, & Graham-Smith, 2016). Moreover, it shifts the GRF vector more in line with the knee position, thus decreasing the moment arm and knee abduction moment (Dos'Santos et al., 2021; Jones et al., 2016). The same principle is true for trunk lean and rotation towards the intended direction (Dempsey et al., 2007). High knee abduction moments are frequently seen in ACL injuries (Della Villa et al., 2020; Lucarno et al., 2021). Therefore, improving frontal plane trunk and foot placement appear to be important strategies to reduce ACL injury risk during sidestep cutting (Dempsey et al., 2007; Dos'Santos et al., 2019; Fox, 2018). So, the frequently observed relationship of frontal trunk and foot placement with knee abduction moment suggests that the changes in the SC group in the current study were meaningful.

4.4. *Implications*

Overall, the results of the current study add to evidence of autonomy on improving motor learning (Chiviacowsky et al., 2012; Wulf & Lewthwaite, 2016). The opportunity to ask for feedback during practice benefited improving the execution of the task. The current study expands on the previous studies showing beneficial effects of self-controlled timing of feedback on accuracy score in relatively simple tasks (e.g., Jalalvand et al., 2019; Kim et al., 2019). Previous work already showed improved movement execution after practising an anticipated double-legged jump-landing task (Benjaminse et al., 2018). In our study, participants practiced another task with sport-specific elements and we showed the additional effects of self-controlled timing of feedback on movement execution in a more unpredictable environment.

All together, evidence is emerging that implementation of self-control, is promising in terms of optimizing motor strategies. We have demonstrated that athletes are able to self-identify their needs to alter their execution. As we did not investigate the interaction between autonomy and other variables (such as video instruction and variable practice), it is not possible to conclude that solely the autonomy on timing of feedback resulted in improved movement execution. However, a combination of autonomy, enhanced expectancies and EF resulted in superior learning relative to the presence of only two variables (Wulf, Lewthwaite, Cardozo, & Chiviacowsky, 2017), arguing for combining different components to optimize learning. As previous research also found beneficial effects of autonomy, as written in the last paragraph, and per definition of our study design, we conclude that autonomy on the timing of feedback had a substantial impact on the current findings. Still, generalisability of the current findings to on-field situations is limited as the current design was limited in preserving the sport-specific context (i.e., opponents, pressure, fatigue etc.) (Bolt, Heuvelmans, Benjaminse, Robinson, & Gokeler, 2021). Furthermore, a low total score will not justify that an athlete is not at risk, as he may still display high-risk cutting deficits, such as high knee abduction or limited knee flexion, on the field (Di Paolo et al., 2022).

From an applied perspective, the present findings suggest that learning a sport-specific task can benefit from giving autonomy to the athletes on the timing of feedback instead of solely using coach-led feedback timing. Coaches and trainers are advised to incorporate some self-control, combined with video instruction and variable practice, in their training and prevention programs.

4.5. *Limitations*

The current study has a number of limitations. One of these limitations is that the CMAS is a scoring tool based on a subjective judgement of an investigator. However, this way of monitoring cutting movement execution in response to training is shown to be reliable and valid (Dos'Santos et al., 2019; Jones et al., 2017). Although a high correlation between CMAS and knee abduction moment exists (Dos'Santos et al., 2019), no specific kinetics are taken into account in this scoring tool. GRF analysis will provide more objective data about the impact on the joints. On the other hand, it is a relatively easy, cost-effective tool to examine movement. Secondly, after inspecting the data we decided to remove data from eight participants because of incorrect task execution, leaving 22 participants for analysis. Although the G*Power analysis indicated a minimum of 28 participants, the effect sizes of the significant results are medium to large ($\eta_p^2 = 0.09–0.39$) and therefore we think that including more participants would not have had a direct influence on the results. Lastly, even though previous research also found positive effects of autonomy on the timing of feedback. It is not possible to generalize our findings to (on-field) practice environments with other tasks, types of instruction and feedback. Therefore, more research is necessary to explore how autonomy on the timing of feedback could be used to optimize practice environments and enhance learning.

4.6. Further research

Research has shown that males and females use different motor control strategies (Fedie, Carlstedt, Willson, & Kernozek, 2010; Schroeder, Peel, Leverenz, & Weinhandl, 2020; Weir et al., 2019) and respond differently to training interventions (Benjaminse et al., 2018). As we only investigated male participants, follow-up research should examine how females respond to similar training interventions. Furthermore, it is thought that participants tend to ask for feedback after relatively good trials, leading to increased perceptions of competence and self-efficacy (Benjaminse et al., 2018; Grand et al., 2015; Kaefer & Chiviacowsky, 2021). The current study did not investigate this and further research should examine if athletes show similar behavior while practising sport-specific tasks. Lastly, our study showed mainly beneficial effects of autonomy in the anticipated condition. Further research is necessary to investigate the effects of autonomy on movement execution in a more challenging, sport-specific environment and on-field testing should be incorporated to examine the transfer as well.

5. Conclusion

The present current provides insight into the effect of autonomy on the timing of feedback on motor learning. Autonomy on the timing of feedback, combined with video instruction and random practice, resulted in better learning and improved movement execution one week after practice compared to the control group. Both groups showed improved movement execution after the training intervention, indicating beneficial effects of the provided feedback. Together, this implies that being involved in determining the timing of video and EF-feedback seems beneficial in optimizing movement execution in SSC and is advised to be implemented in ACL injury prevention programs.

Funding acquisition

Not applicable

CRediT authorship contribution statement

E.M. Nijmeijer: Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **M.T. Elferink-Gemser:** Writing – original draft, Writing – review & editing. **S. McCrory:** Writing – review & editing. **N. Cortes:** Conceptualization, Formal analysis, Methodology, Writing – review & editing, Visualization. **A. Benjaminse:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Data curation, Project administration.

Declaration of competing interest

None of the authors have any conflicts of interest that are relevant to this work.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Julia Bombach and Jouke Bosma for their help in study design and data acquisition, Dr. Harjiv Singh for his assistance in designing the test protocol and Dr. Matthias Kempe for his advice about the analysis.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. EF feedback cues

Frontal plane	Sagittal plane
Wide lateral leg plant	Backward inclination of the trunk:
- "Remember, keep you shoes within the width of your shorts"	- "On this next trial, keep the marker on your shirt pointing towards the floor"
Hip in an initial internally rotated position	Trunk upright or leaning back throughout contact
- "When you are cutting, you may want to point the tip of your shoe towards the finish/gates"	- "When contacting the force plate, let's try to maximize you focus on the lights/gates"
Initial knee valgus position and inwardly rotated foot position/excessive knee valgus motion during contact	Limited knee flexion during final contact
- "When you are cutting, point your shoes/the marker towards the finish/gates"	- "Try propelling like a spring/rocket as soon as you make contact with the force plate" - "Push off as forcefully as possible when you make contact with the force plate"
Frontal plane trunk position relative to intended direction	
- "Concentrate on the finish"	

Appendix B. CMAS scoring tool

Camera	Item	Observation	Score
Penultimate contact			
Side	Clear PFC braking strategy (at IC) • Backward inclination of the trunk • Large CoM to CoP position – anterior placement of the foot • Effective deceleration – heel contact PFC	Y/N	Y = 0 N = 1
Final contact			
Side	Trunk upright or leaning back throughout contact (not adequate trunk flexion displacement) (at IC and over WA)	Y/N	Y = 1 N = 0
Side	Limited knee flexion during final contact (stiff) $\leq 30^{\circ}$ (over WA)	Y/N	Y = 1 N = 0
Front	Wide lateral leg plant (approx. > 0.35 m – dependent on subject anthropometrics) (at IC)	Y/N	Y = 2 N = 0
Front	Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb, Upright, or Medial (at IC and over WA)	L/TR/U/M	L/TR = 2 U = 1 M = 0
Front	Hip in an initial internally rotated position (at IC)	Y/N	Y = 1 N = 0
Front	Initial knee 'valgus' position (at IC)	Y/N	Y = 1 N = 0
Front	Foot not in neutral foot position (at IC) Inwardly rotated foot position or externally rotated foot position (relative to original direction of travel)	Y/N	Y = 1 N = 0
Front	Excessive knee 'valgus' motion during contact (over WA)	Y/N	Y = 1 N = 0

PFC: penultimate foot contact; IC: initial contact; CoM: centre of mass; CoP: centre of pressure; WA: weight acceptance; Y: yes; N: no; L: lateral; TR: trunk rotation; U: upright; M: medial.

Appendix C

Table C.1
Mean ± std scores of CMAS items.

	Group	Condition	Wide lateral leg plant	Frontal trunk position relative to intended direction	Hip in an initial internally rotated position	Initial knee valgus	Foot not in neutral foot position	Excessive knee valgus during contact	Clear PFC braking strategy	Trunk upright or leaning back throughout contact	Limited knee flexion during final contact	Total
Pre-test	SC	Anticipated	0.00 ± 0.00	**0.63 ± 0.65**	0.04 ± 0.19	0.00 ± 0.00	**0.46 ± 0.50**	0.17 ± 0.38	0.65 ± 0.48	0.75 ± 0.74	0.31 ± 0.47	2.96 ± 1.06
		Unanticipated	0.00 ± 0.00	1.48 ± 0.62	0.18 ± 0.39	0.02 ± 0.13	0.66 ± 0.48	0.04 ± 0.18	0.70 ± 0.46	0.41 ± 0.50	0.05 ± 0.23	3.53 ± 0.81
		Total	0.00 ± 0.00	1.06 ± 0.77	0.11 ± 0.31	0.01 ± 0.10	0.57 ± 0.50	0.10 ± 0.30	0.67 ± 0.47	0.57 ± 0.50	0.18 ± 0.39	3.24 ± 0.98
	YK	Anticipated	0.00 ± 0.00	0.49 ± 0.54	0.00 ± 0.00	0.13 ± 0.35	0.67 ± 0.48	0.06 ± 0.24	0.35 ± 0.48	0.80 ± 0.40	0.12 ± 0.33	2.60 ± 0.99
		Unanticipated	0.04 ± 0.27	1.04 ± 0.82	0.02 ± 0.14	0.17 ± 0.38	0.80 ± 0.41	0.04 ± 0.19	0.87 ± 0.34	0.50 ± 0.50	0.06 ± 0.23	3.52 ± 1.32
		Total	0.02 ± 0.20	0.77 ± 0.75	0.01 ± 0.10	0.15 ± 0.30	0.73 ± 0.44	0.05 ± 0.21	0.62 ± 0.49	0.64 ± 0.48	0.09 ± 0.28	3.06 ± 1.25
Immediate-post test	SC	Anticipated	0.00 ± 0.00	0.27 ± 0.54	0.23 ± 0.42	0.02 ± 0.14	0.00 ± 0.00	0.00 ± 0.00	0.63 ± 0.49	0.54 ± 0.49	0.31 ± 0.47	1.93 ± 1.07
		Unanticipated	0.04 ± 0.27	1.23 ± 0.82	0.34 ± 0.48	0.02 ± 0.14	0.26 ± 0.45	0.06 ± 0.23	0.70 ± 0.46	0.30 ± 0.46	0.08 ± 0.27	3.07 ± 1.20
		Total	0.04 ± 0.27	0.77 ± 0.85	0.29 ± 0.45	0.02 ± 0.14	0.14 ± 0.35	0.03 ± 0.10	0.66 ± 0.47	0.42 ± 0.50	0.19 ± 0.39	2.51 ± 1.27
	YK	Anticipated	0.00 ± 0.00	0.22 ± 0.42	0.02 ± 0.14	0.02 ± 0.14	0.12 ± 0.33	0.00 ± 0.00	0.29 ± 0.46	0.80 ± 0.40	0.18 ± 0.39	1.77 ± 1.10
		Unanticipated	0.00 ± 0.00	0.80 ± 0.80	0.08 ± 0.27	0.16 ± 0.37	0.47 ± 0.50	0.06 ± 0.24	0.84 ± 0.37	0.55 ± 0.50	0.20 ± 0.40	3.05 ± 1.13
		Total	0.00 ± 0.00	0.51 ± 0.70	0.05 ± 0.22	0.09 ± 0.29	0.29 ± 0.46	0.03 ± 0.17	0.57 ± 0.50	0.68 ± 0.47	0.19 ± 0.39	2.40 ± 1.28
Retention test	SC	Anticipated	0.00 ± 0.00	**0.15 ± 0.36**	0.26 ± 0.44	0.00 ± 0.00	**0.02 ± 0.15**	0.02 ± 0.15	0.55 ± 0.50	0.53 ± 0.50	0.23 ± 0.43	1.69 ± 0.94
		Unanticipated	0.00 ± 0.00	0.88 ± 0.80	0.37 ± 0.49	0.06 ± 0.23	0.11 ± 0.32	0.04 ± 0.19	0.87 ± 0.34	0.35 ± 0.48	0.06 ± 0.23	2.71 ± 1.13
		Total	0.00 ± 0.00	0.53 ± 0.73	0.32 ± 0.47	0.03 ± 0.17	0.07 ± 0.26	0.03 ± 0.17	0.72 ± 0.45	0.44 ± 0.50	0.14 ± 0.35	2.20 ± 1.16
	YK	Anticipated	0.00 ± 0.00	0.26 ± 0.44	0.13 ± 0.34	0.00 ± 0.00	0.30 ± 0.47	0.02 ± 0.15	0.52 ± 0.51	0.85 ± 0.36	0.35 ± 0.48	2.40 ± 1.07
		Unanticipated	0.00 ± 0.00	0.92 ± 0.77	0.23 ± 0.42	0.08 ± 0.28	0.42 ± 0.50	0.02 ± 0.14	0.88 ± 0.33	0.56 ± 0.50	0.21 ± 0.41	3.27 ± 0.96
		Total	0.00 ± 0.00	0.60 ± 0.71	0.18 ± 0.39	0.04 ± 0.20	0.36 ± 0.48	0.02 ± 0.15	0.70 ± 0.46	0.70 ± 0.46	0.28 ± 0.45	2.83 ± 1.10

SC; self-control group, YK; yoked group, IC; initial contact, PFC; penultimate foot contact, bold; main changes of the SC group from pre- to retention test.

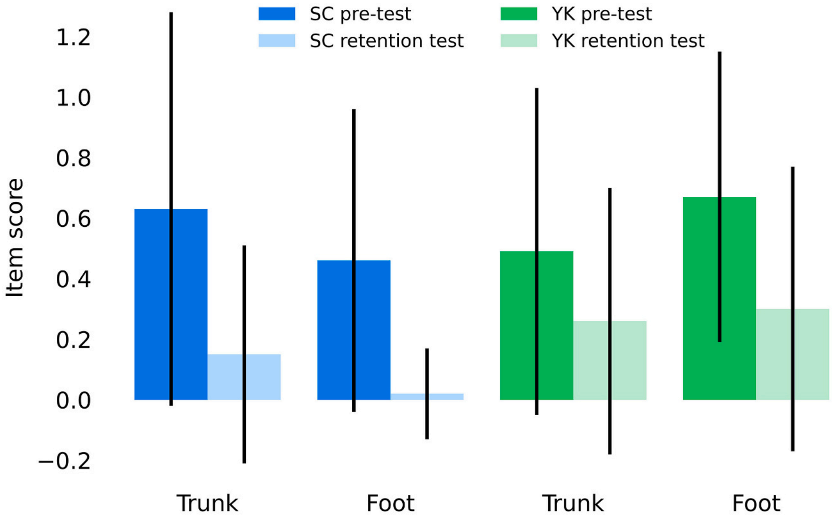

Fig. C.1. Mean ± std. scores of two items. Trunk refers to 'Frontal plane trunk position relative to intended direction' and Foot refers to 'Foot not in neutral foot position (at IC)' of SC (left) and YK group (right).

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