Title: Resolution of low-velocity control in golf putting differentiates professionals from amateurs

Running title: Resolution of low-velocity control in golf putting

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Abstract

It is difficult for humans to apply small amounts of force precisely during motor control. However, experts who have undergone extended training are thought to be able to control low-velocity movement with precision. We investigated the resolution of motor control in golf putting. A total of 10 professional and 10 high-level amateur golfers participated. Putting distances were 0.6 – 3.3 m, in increments of 0.3 m. We measured the impact velocity and the club-face angle at impact, and the acceleration profile of the downswing. The professionals showed significantly smaller coefficients of variation with respect to impact velocity and smaller root mean square errors in relation to acceleration profiles than did the amateurs. To examine the resolution of motor control for impact velocity, we investigated intra-participant differences in the impact velocity of the club head at two adjacent distances. We found that professionals had higher velocity precision when putting small distance intervals than did amateurs. That is, professionals had higher resolution of low-velocity control than did high-level amateurs. Our results suggest that outstanding performance at a task involves the ability to recognise small distinctions and to produce appropriate movements.

Keywords:

fine motor control, precision, peak velocity, overlap, differentiation

1. Introduction

Numerous studies of human movement have examined perception and cognitive skills as well as ways in which the performances of experts differ from those of novice and intermediate-level participants to understand what skillfulness entails and how it is achieved. Overall, the findings indicate that experts acquire environmental information more effectively (Mann, Williams, Ward & Janelle, 2007; Savelsbergh, Williams, van der Kamp & Ward, 2002), and their subsequent decision-making (Lex, Essig, Knoblauch & Schack, 2015; Williams, Hodges, North & Barton, 2006) and performance (e.g., Delay, Nougier, Orliaguet & Coello, 1997; Sim & Kim, 2010; Wagner, Pfusterschmied, Klous, von Duvillard & Müller, 2012) are more accurate than those of novices. In contrast, high-level amateur players who have undergone long-term training may occasionally achieve results similar to those of professional players. It is likely that performance differences exist between professionals and high-level amateurs; however few studies have compared performance in elite and high-level amateur athletes (Landlinger, Stöggl, Lindinger, Wagner & Müller, 2012). It is important to determine the actions high-level amateurs, who have invested a considerable amount of time practicing, and compete in tournaments, need to take to approach professional levels.

Experts are able to perceive subtle differences in the environment (Bhatara, Tirovolas, Duan, Levy & Levitin, 2011) and control their movements with extreme precision (Kinoshita, Furuya, Aoki & Altenmüller, 2007). Both of these abilities are attributes that are required for putting in golf. The putt must generate club-head velocity in the direction of the intended target (Hume, Keogh & Reid, 2005). Previous studies have identified four variables related to velocity control corresponding to the distance to the target (Craig, Delay, Grealy & Lee, 2000) and examined differences between professionals and novices (Hume et al., 2005). Differences between experts and novices in putting have been investigated in terms of accuracy defined as error from the target. Experts achieved higher accuracy with a lower impact velocity (Delay et al, 1997; Sim & Kim, 2010). Additionally, from the perspective of precision, defined as reproducibility of movement, Mathers and Grealy (2014) found that experts were consistently able to control velocity at a constant distance. Similarly, consistency in stroke direction at a constant distance, assessed in terms of the face angle, putter path, and impact point, has been shown to be higher among elite golfers than amateurs (Karlsen, Smith & Nilsson, 2008).

However, the long putting distance intervals (1, 2, 3 and 4 m) used in previous studies cannot detect subtle differences in perception and precise movement control (e.g., perception and movement clearly differ for 1-m and 2-m putts) between experts and high-level amateurs. An investigation of the relationship between distance and success rate in professional golf tournaments conducted by the Professional Golf Association assessed successful putts at short distances between 0.6 and 6 m in 0.3-m intervals and found a rapid decline in the rate of success as the distance increased from 0.6 m (approx. 95%) to 3 m (approx. 30%) (Gelman & Nolan, 2002; Pelz, 1989, 2000). These distances are critical for producing a low score (Pelz, 1989, 2000). Thus, subtle difference in perceptual motor control between experts and high-level amateurs can be found in these short distance intervals.

Furthermore, putting is an excellent example of fine-tuned motor control because it requires the adjustment of low levels of force in response to the distance from the target. When putting, the forearm uses approximately 3% of the maximum voluntary contraction (MVC) force (Tanaka & Sekiya, 2006). In golf, it is necessary to produce small changes in velocity and to hit the ball various distances while making adjustments in force, which require sensitivity to subtle differences in distance and high accuracy and precision in low-velocity control. We defined this ability as fine resolution. We hypothesised that players who did not possess perception and movement control resolution would not achieve superior results because the target of each putt changes slightly (even when the precision is high). We further hypothesised that there would be more overlap between two adjacent distances at small distance intervals in amateurs than professionals (i.e., the overlap between intra- and inter-distance variabilities). To test our hypotheses, we constructed a hole comparable to a hole on an actual golf course to measure putting accuracy between 0.6 and 3.3 m at 0.3-m intervals.

Impact velocity, the face angle at impact, and the root mean square error (RMSE) of the acceleration profile were selected as independent variables to explain resolution in motor control. These variables were chosen because the outcome of a putt is largely determined by the angle (Karlsen et al., 2008; Pelz, 2000) in the mediolateral direction (Figure 1) and velocity at impact (Craig et al., 2000; Dias et al., 2014; Hume et al, 2005; Mathers & Grealy, 2014) in the anteroposterior direction (Figure 1). We measured the RMSE of the acceleration profile to determine whether the motor-control pattern used to generate the velocity at impact was constant. We predicted that we would not observe differences in accuracy, defined as the values obtained from hitting at the same distance multiple times, between groups in a laboratory setting, such as our experiment. However, we hypothesised that we would observe differences in resolution between professionals and high-level amateurs owing to differences in precision.

The purpose of this study was to compare the degree of resolution in motor control during golf putting between professionals and high-level amateurs by comparing the kinematics of the club head. Our findings provide novel insights into the resolution of fine motor control for coaches, practitioners and sports science researchers.

2. Methods

2.1. Participants

The sample consisted of 10 professional golfers (5 men and 5 women) and 10 amateur golfers (5 men and 5 women). The average age of the professional golfers was 34.4 ± 4.9 years, and they had been playing golf for 18.7 ± 3.1 years. The average age of the amateur golfers was 41.5 ± 11.5 years, and they had been playing golf for 15.1 ± 6.5 years. The amateur golfers who participated in this study were high-level players who participated in competitions, with an average handicap of 6.3 ± 2.5. All participants provided informed consent. The experimental procedures were approved by the Internal Review Board of the Research Center of Health, Physical Fitness and Sports at Nagoya University and conformed to the principles expressed in the Declaration of Helsinki.

2.2. Apparatus

A single layer of artificial turf manufactured for golf putting (K-80, Kiitos Co., Ltd, Tokyo, Japan) was stretched across a flat platform made of wood; this platform was 6.00 m long × 1.82 m wide × 0.30 m high, and contained a standard golf hole (10.8 cm in diameter and approximately 15 cm deep). The centre of the hole was 1.20 m from the end edge and 0.91 m from the side edge of the putting platform (see Figure 1). Using an instrument called a Stimpmeter, which indicates how easily a ball rolls over turf by measuring how many feet it travels after being released from the device, we obtained a Stimp rating of 9 ft, which is the optimal speed normally observed at golf courses.

We recorded the kinematics of each putt using six optical motion-capture system cameras (Qualysys oqus 300, Qualisys AB, Sweden). The sampling frequency of the cameras was 250 Hz. We attached 10-mm markers to the toe and heel of the putter head, and digitised the positions of both. The mean calibration error differed for each participant because calibration was carried out prior to each participant's session. The root mean square errors for both the static and dynamic calibrations were lower than 1.5 mm. All participants used the same ball (SRIXON Z-STAR XV, Dunlop Sports Co., Ltd, Kobe, Hyogo, Japan), but their own putters.

2.3. Procedure

After participants had provided informed consent, they received instructions regarding a waiting position located at the rear of the putting platform (see Figure 1). The rules stated that after each putting attempt, the participant was to stand in the waiting position facing away from the ball until he /she received a signal from the experimenter indicating that it was permissible to turn around and putt the ball that had been put in place.

We set 10 distances between 0.6 m and 3.3 m, in increments of 0.3 m. After taking 12 practice putts from a distance of 4.0 m, each participant took 100 trial putts (in sets of 10 putts). The various distances occurred in random order, and no information about the distance to the hole was explicitly conveyed to the participants. Participants were not placed parallel to the major axis of the putting mat (Lee, Linkenauger, Bakdash, Joy-Gaba, & Proffit, 2011). Instead, their putts occurred at an angle of $\theta = 4.95$ degrees relative to the major axis (see also Figure 1). The goal for each participant was to sink the ball in one putt. Participants were offered the opportunity to rest between sets.

****Figure 1 near here****

2.4. Dependent variables

2.4.1. Putting score

One point was awarded if the participant sank the putt on the first try, and zero points were awarded if the putt was not sunk on the first attempt.

2.4.2. Kinematics

The digitised data were smoothed with a fourth-order Butterworth filter, using a 5-Hz cut-off frequency, prior to calculation. This cut-off frequency was determined based on the root mean square of the residual error between the original and smoothed data (Jackson, 1979; Winter, 1990). The putting movement was divided into backswing, downswing, ball impact and follow-through (Couceiro, Dias, Mendes & Araújo, 2013; Dias & Couceiro, 2015; Pelz, 2000).

Impact velocity was defined as the peak velocity of the club head. We established that the peak velocity occurred during the downswing immediately before impact and the velocity profile dropped rapidly at impact for all trials in all participants (i.e., within 0.004 s before impact, given that measurements were recorded at 250 Hz). Using the velocity profile, we defined the completion of the backswing as the point prior to the peak velocity at which the velocity transitioned to a value greater than zero (i.e. going from negative to positive velocity). We defined the beginning of the backswing as the point prior to the completion of the backswing at which the acceleration curve crossed zero for a second time; this definition reflects the fact that until completion of the backswing there are acceleration and deceleration peaks in the direction opposite to the hitting direction.

We calculated the club-face angle at impact, which we defined as a relative value obtained by subtracting the face angle at impact velocity from the face angle at the beginning of the backswing. Because the face angle opens and closes in the mediolateral direction during the stroke (Karlsen et al., 2008), it is in fact slightly more open immediately before impact (within 0.004 s) than it is immediately after impact, and it is different from the ball's actual angle of launch. However, because we calculated the club-face angle using a consistent definition across all participants, this value can be regarded as sufficiently reliable. In addition, we calculated the coefficients of variation (CV) for the face angle and peak velocity.

To measure variability in the acceleration profile of the downswing further, which involves the motor-control process that is responsible for the impact velocity, we normalised the acceleration and calculated the RMSE. To compare variability in acceleration with time and magnitude scales that differed by distance and trial, we normalised not only the time but also the magnitude of the acceleration, calculated the RMSE (see Figure 2), and compared groups (professionals and amateurs).

****Figure 2 near here****

2.5. Data analysis

To investigate resolution in motor control, we assessed the relationships among the 2 levels of group and 10 levels of distance using a mixed-design two-factor analysis of variance (ANOVA) with respect to the average face angle at impact, average impact velocity, the CV for face angle and impact velocity, normalised acceleration profile RMSE and putting scores. The results for multiple comparisons of distance are shown in a supplementary file on Figshare (Data Citations 1-4: Figshare http://figshare.com/s/708d01d67d0c11e5bf9f06ec4bbcf141). Putting distance was a repeated-measures factor. Bonferroni's method was used to correct for multiple-comparison testing. When Mauchly's sphericity test indicated that we could not assume equal distributions with regard to the repeated factors in the analysis of variation, we applied the Greenhouse-Geisser correction. The alpha level for significance was set at $p < .05$. In addition, we calculated the f and ω effect-size indices (Faul, Erdfelder, Lang, & Buchner, 2007).

To identify the extent to which club-head velocity can be finely controlled, we performed a one-factor ANOVA for each of the participants, with the 10 levels of distance as the factor. The results of each participant's one-factor ANOVA are shown in a supplementary file on Figshare (Data Citation 5: Figshare http://figshare.com/s/708d01d67d0c11e5bf9f06ec4bbcf141). We then performed a post hoc test in which we categorised cases into those where a significant difference was observed between two adjacent distances and those in which none was observed. Cases where a significant difference was observed between two adjacent distances were judged to reflect the application of fine control. We judged cases where no difference was observed between two adjacent distances as failures to apply fine control; we defined these as cases of velocity overlap for the purpose of further analysis, as illustrated in Figure 3. Next, to compare levels of expertise, we counted the number of distinguishable adjacent distances for each group (i.e. adjacent distances that did not involve velocity overlap). For example, suppose that there was a significant difference at all distances for all participants; in such a case, the number for that group would be 100 (10 distances × 10 participants). Using a chi-square test, we compared the scores thus obtained between the two groups.

****Figure 3 near here****

3. Results

3.1. Putting score

Table 1 shows the average putting score for each group. The results of the two-factor ANOVA for putting scores neither show a significant interaction between group and distance, nor was the main effect of group significant. However, the main effect of distance was significant ($F(3.93, 70.66) = 27.73, P = 1.00 \times 10^{-13}, f = 1.24$) (Data Citations 1).

****Table 1 near here****

3.2. Face angle

Figure 4 shows the average values and coefficients of variation for face angle. The results of the two-factor ANOVA for average face angle showed a significant interaction between group and distance ($F(3.79, 28.81) =2.58, P =.048, f =0.58$). The main effect of group was not significant, whereas the main effect of distance was significant ($F(3.79, 28.81) = 3.85, P =.008, f =0.71$) (Data Citations 2). The results of the two-factor ANOVA for face-angle CV showed no significant interaction between group and distance. The main effects of group and distance were not significant.

****Figure 4 near here****

3.3. Impact velocity

Figure 5 shows the values for average velocity at impact and the CV. The results of the two-factor ANOVA for impact velocity did not show a significant interaction between group and distance, and the main effect of group was not significant. However, the main effect of distance was significant ($F(2.07, 37.22) = 932.39, P =9.91 \times 10^{-33}, f =7.20$) (Data Citations 3). The results of the two-factor ANOVA for impact velocity CV showed no significant interaction between group and distance. The main effect of group was significant ($F(1,18)=21.29, P =2.15 \times 10^{-4}, f =1.08$) ; professional players showed a lower CV in impact velocity than did amateurs. The main effect of distance was also significant ($F(4.50, 81.05) = 4.38, P =.002, f =0.49$) (Data

Citations 4).

Figure 6(a) shows the degree of fine control over impact velocity applied by each participant, defined using the results of a one-factor ANOVA with 10 levels of distance as the factor, followed by Bonferroni’s multiple comparisons (refer to Data Citations 5 for detailed ANOVA results for each participant). To examine differences in expertise, we calculated the number of distinguishable distances for each participant and compared these scores across groups using a chi-square test. The difference between groups was found to be significant $(\chi^2 =12.81, P < .05, \omega=0.25)$, and the results of the residual analysis showed that professionals were able to discriminate distances differing by 0.3-m intervals more often than amateurs (see Figure 6(b)).

****Figure 5 near here****

****Figure 6 near here****

3.4. RMSE of acceleration profiles

Figure 7 shows the values for the root mean square error for the normalised acceleration profiles. The results of a two-factor ANOVA showed no significant interaction. The main effect of group was significant; professionals had lower RMSE values for their acceleration profiles than did amateurs $(F(1, 18) =7.35, P =.014, f =0.63)$. The main effect of distance was not significant.

****Figure 7 near here****

4. Discussion

Our aim was to investigate the degree of resolution in fine motor control during golf putting by comparing the club-head kinematics of professional versus high-level amateur golfers.

We did not observe differences in putting scores between professionals and amateurs. One reason for this may be that the amateurs participating in our research were high-level golfers who frequently take part in competition. Additionally, the conditions, which involved putting indoors on level, artificial turf, may not have been sufficiently difficult to highlight differences in scoring between the two groups. However, there were differences with regard to the resolution of motor control between the two groups.

The analysis of impact velocity revealed no differences between professionals and high-level amateurs. However, the professionals had a lower impact-velocity CV than did the amateurs. Our findings support our hypothesis that expertise would have an effect on precision but not accuracy. Furthermore, our findings support those of Mathers and Grealy (2014) showing that experts were highly consistent in their ability to control velocity to achieve the target. Decreased variability in movement kinematics is thought to be a characteristic of expert’s performance, such as baseball pitching (Fleisig, Chu, Weber & Andrews, 2009), the basketball free-throw (Button, MacLeod, Sanders & Coleman, 2003), gymnastics swinging (Hiley, Zuevsky & Yeadon, 2013) and the handball standing throw (Wagner et al., 2012). Our findings suggest that professionals and high-level amateurs differ in relation to precision, but not average performance.

Our analysis of the average face angle and related CV values revealed no expertise-related differences between professionals and amateurs, suggesting that expertise does not have an impact on variability of movement in the mediolateral direction at impact. Thus, our high-level amateur participants achieved the same results as the professionals.

We investigated the resolution of low-velocity force control in the golfers. Several studies have investigated the ability to control submaximal voluntary contraction force relative to maximal voluntary contraction force (e.g., 20–80%) in movements involving a comparatively large amount of force, such as jumping (Lees, Vanrenterghem & Clercq, 2004; Sahaly, Vandewalle, Driss & Monod, 2001; Vanrenterghem, Lees, Lenoir, Aerts & Clercq, 2004; van Zandwijk, Bobbert, Munneke & Pas, 2000). However, the phenomenon how people are able to finely adjust small amounts of force are not known; moreover, no studies have investigated whether precision is improved by long-term practice. With regard to impact-velocity resolution, we found that professionals had fewer instances of overlap in impact velocity between two adjacent distances than did amateurs. That is to say, professionals showed finer precision in velocity at short distance intervals than did amateurs. We consider these results to resemble those of Kinoshita et al. (2007), who found that pianists were able to modulate extremely low levels of force. Our findings suggest that high resolution is a general characteristic of professional golfers. At least, the high resolution in the motor control of professionals implies that they also possess high resolution in perception. We were not able to determine whether low resolution in high-level amateurs was the result of low-perception resolution or low movement-control resolution. Further studies are planned to clarify this issue.

In addition, the RMSE analysis of acceleration profile during downswing showed that professionals exhibited less variability than did amateurs, indicating that professionals were able to produce more consistent downswing movements and impact velocity than amateurs. To our knowledge, few studies have investigated mean (Cooke, Kavussanu, McIntyre & Ring, 2010; Cooke, Kavussanu, McIntyre, Boardley & Ring, 2011) and maximum acceleration (Dias et al., 2014) of the downswing during putting; however, some studies have investigated the acceleration profile during putting (Fairweather, Button & Rae, 2002). Our acceleration profile analysis revealed that professionals exhibited less variability in acceleration compared with amateurs, indicating that, in professionals, the motor-control pattern during downswing within the same distance was consistent. This finding supports our general conclusion that professionals are capable of finer resolution in force adjustments.

Our findings suggest that the key to overcoming the barrier that separates amateurs from professionals is related to fine control over velocity. Our participants were required to sink the ball in one putt. That is, the speed of the ball could be changed as slightly fast or slow only if it reached the hole. Thus, there was redundancy in velocity control in this task. However, the professionals exerted finer control of club-head velocity than was required for the task. This may be a useful training technique for putting. When practicing in a relatively stable environment, golfers who aspire to play at a high level should not simply make putts but, rather, focus on the speed at which the ball rolls into the hole. For example, golfers should aim to control the ball speed to let it tap the back of the hole or sink in on the final roll. Such efforts to precisely control ball speed in a controlled environment may increase the rate of success on the sloping greens.

We conclude that the resolution of low-velocity control during putting differentiates professional from amateur golfers. Our research, focused on putter-head velocities that required modulation between 2 % and 2.5 % velocity over putting distance (50 m/s was regarded as 100% because it is the average velocity at impact after a full swing by male professional golfers). Our research results indicate that professionals do perceptually differentiate between subtle differences in distance and can produce accurate and precise movements in response to such small distinctions. According to the Oxford English Dictionary, the original meaning of the word “skill” pertained to the differentiation of thread or cut cloth when weaving, and in Northern European languages, the word is used not to mean “proficiency” but rather to indicate distinction or difference. To put it in everyday terms, outstanding performance at a task is the ability to recognise small distinctions and to produce movements in response to them.

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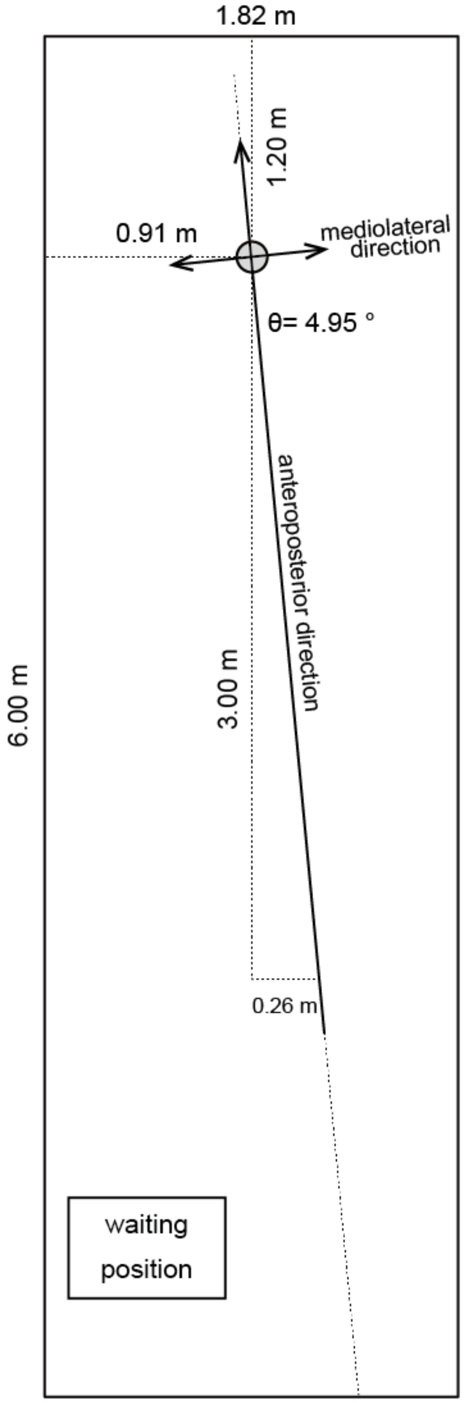

Figure 1. Putting platform.

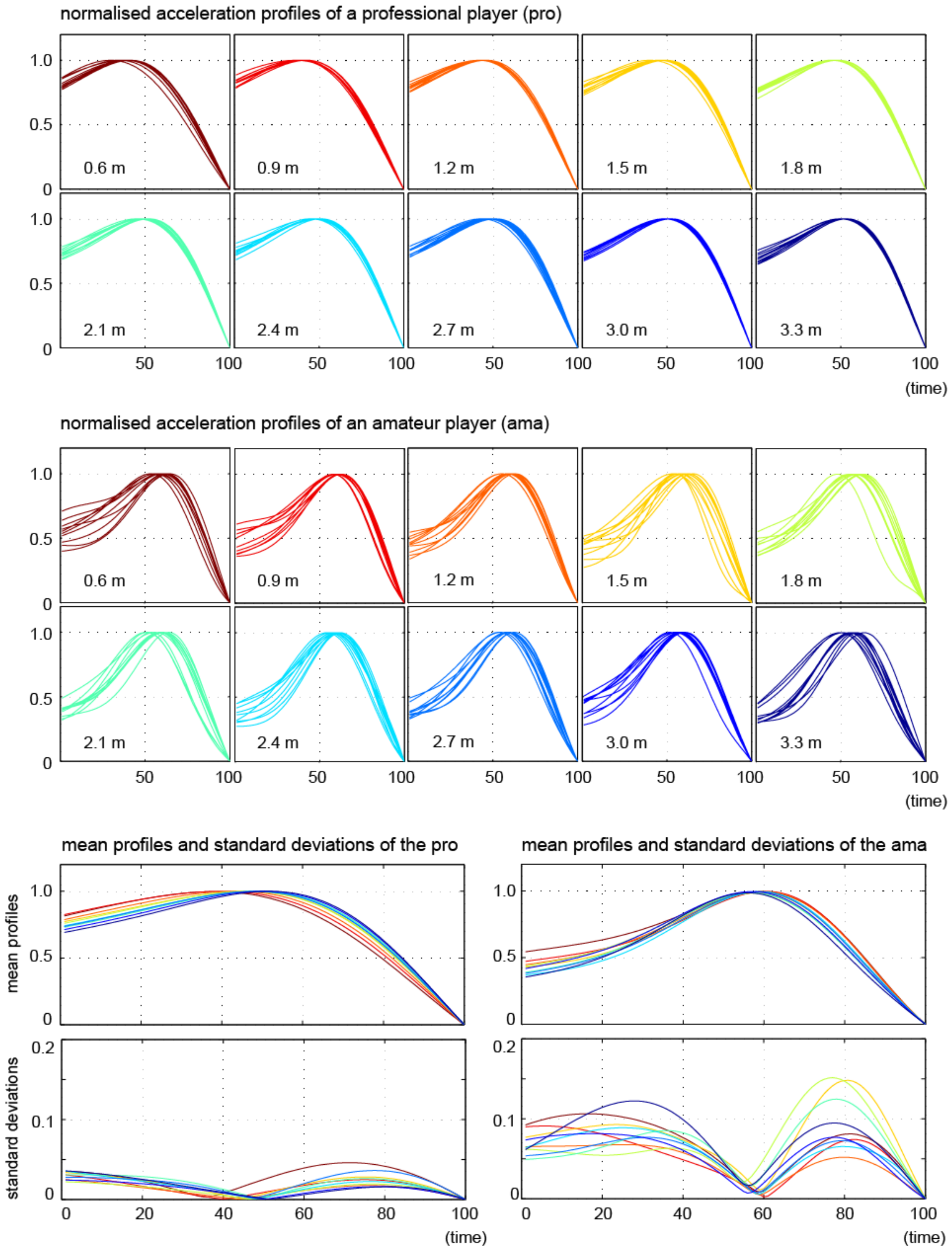

Figure 2. Examples of the normalised acceleration profile of professional and amateur players. These show normalised acceleration profiles for a professional and an amateur player. The top set shows acceleration profiles for the professional, the middle set shows acceleration

profiles for the amateur, the lower-left charts show mean profiles and standard deviations at each distance for the professional; the lower-right charts show the mean profiles and standard deviations at each distance for the amateur.

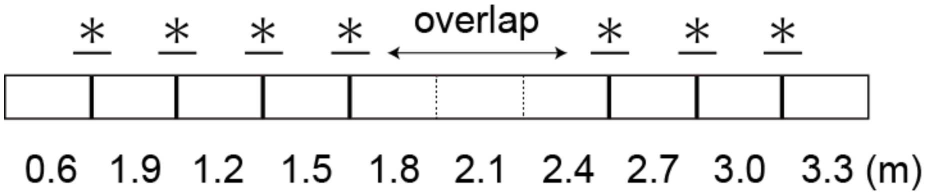

Figure 3. Definition of overlap. This figure illustrates how "velocity overlap" is defined in our research. We defined velocity overlap as a case in which no differences exist between two adjacent distances in a multiple comparison after a one-factor analysis of variance. In this figure, there are no differences in impact velocity between the 1.8 m and 2.1 m distances or between the 2.1 m and 2.4 m distances indicating an overlap at these distances.

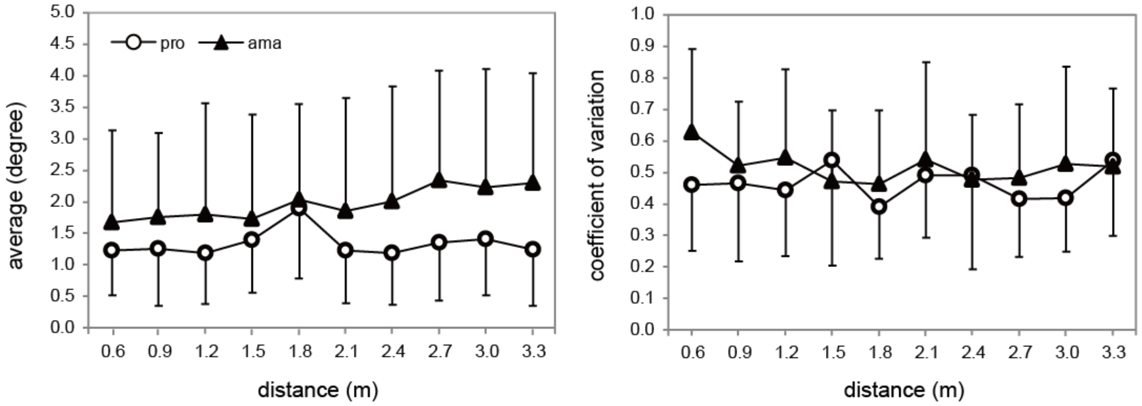

Figure 4. Face angle and face angle CV at impact. The left chart shows average face-angle values for professionals and amateurs. The right shows the coefficients of variation (CV) of face angles for professionals and amateurs.

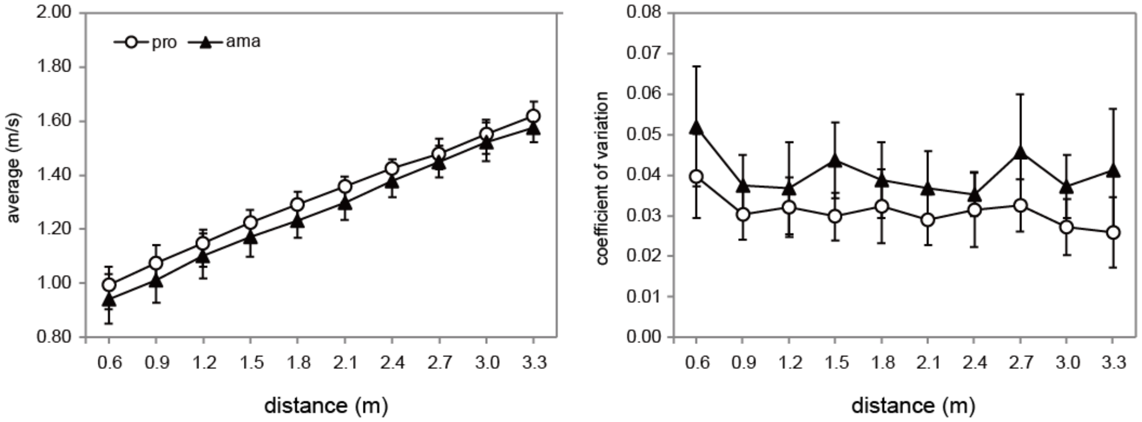

Figure 5. Impact velocity and impact velocity CV. The left chart shows average values and standard deviations of impact velocity for professionals and amateurs. The right chart shows the average coefficients of variation (CV) in impact velocity, and standard deviations for professionals and amateurs.

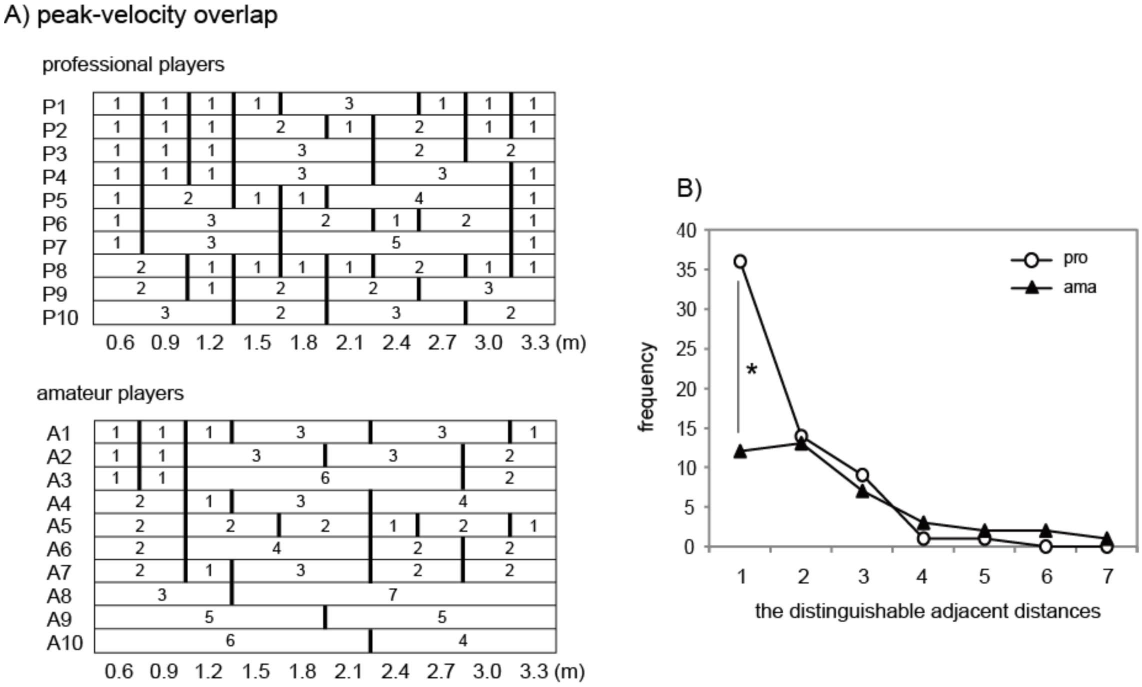

Figure 6. Impact-velocity overlap for professional and amateur players. Figure 6(a) shows each participants’ overlap in impact velocity. Figure 6(b) shows a comparative analysis of the number of distinguishable adjacent distances for each group.

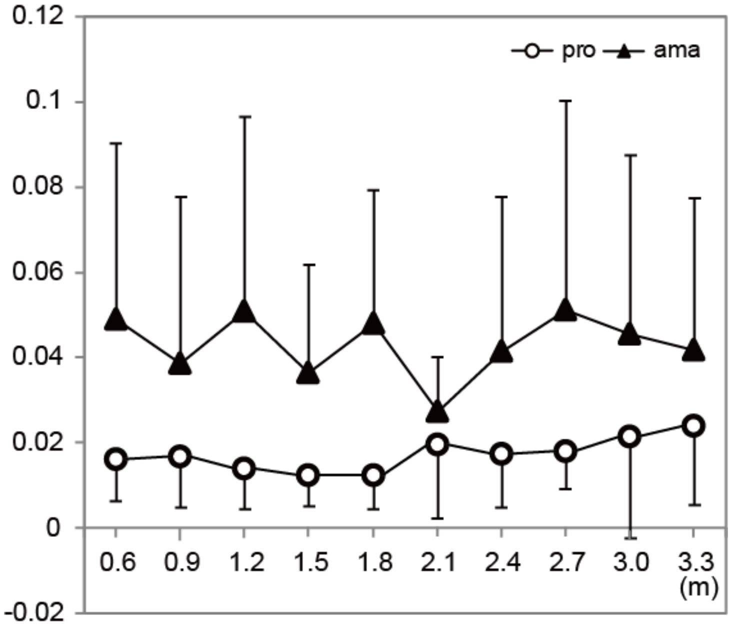

Figure 7. Normalised acceleration profiles RMSE.

Table 1. Putting scores for each group.

distance	professional (sd)		amateur (sd)	
0.6 m	0.99	(0.03)	1.00	(0.00)
0.9 m	0.98	(0.04)	1.00	(0.00)
1.2 m	0.99	(0.03)	0.99	(0.03)
1.5 m	0.97	(0.05)	0.96	(0.05)
1.8 m	0.91	(0.11)	0.94	(0.07)
2.1 m	0.77	(0.13)	0.91	(0.07)
2.4 m	0.73	(0.21)	0.81	(0.17)
2.7 m	0.72	(0.23)	0.72	(0.17)
3.0 m	0.86	(0.14)	0.78	(0.13)
3.3 m	0.62	(0.22)	0.60	(0.14)