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Differences between experts and novices in kinematics and accuracy of golf putting

Mikyong Sim*, Jin-Uk Kim

Department of Physical Education & Sports, Kunsan National University, Republic of Korea

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ABSTRACT

In this study, golf-putting movements were examined under three goal distances (short, 1.7 m; middle, 3.25 m; long, 6 m), two different putter weights (500 g, 750 g), and two levels of expertise (5 experts, 5 novices). The study's aim was to identify differences in kinematics and accuracy between expert and novice golfers. The results demonstrated that experts achieved higher accuracy with lower impact velocity than novices. In addition, while novices showed symmetrical movements, experts exhibited asymmetrical movements, which were achieved by modulating their movement time and amplitude differently from novices. These results demonstrated differences in relative timing, relative amplitude and velocity, but no difference in time-to-contact between novices and experts. The results reaffirmed the role of prior learning and supported the hypothesis of [Manoel and Connolly \(1995\)](#) that motor learning is a hierarchical process organized at both macroscopic and microscopic levels.

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1. Introduction

Golf putting is an impact movement in which force is applied by a putter to a stationary ball. If the right amount of force is transmitted to the ball in the appropriate direction, the ball will be hit at or close to the target, and putting will be characterized by a high degree of accuracy. According to the impulse variability model ([Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979](#)), to send a ball close to the target, the magnitude of the impulse that a putter applies to the ball on impact must be precise

* Corresponding author. Tel.: +571 882 4347.

E-mail address: mksim09@gmail.com (M. Sim).

and appropriate. In putting, the moment of impact is extremely brief and can be ignored (Cochran & Stobbs, 1968). Therefore, the velocity of the putter at impact is a very important factor in achieving accuracy, but this also raises questions about the optimal velocity for accurate putting.

The impulse variability model also suggests that impulse variability is related directly and linearly to movement amplitude, and related inversely and linearly to movement time. As such, movement distance determines the impulse magnitude and its variability if movement time is constant. As long as movement distance and time remain constant, neither impulse magnitude nor variability will change (Delay, Nougier, Orliaguet, & Coello, 1997; Schmidt et al., 1979). Therefore, one would expect no velocity difference between groups with different levels of expertise for identical targets if their putting movements are isochronous.

It appears that the impulse variability model explains movements solely when performers have the same level of experience and skill. That is, the impulse variability model is mute on the issue of motor learning.

In discussing the development of skilled action, Manoel and Connolly (1995) argued that it is a hierarchical process organized at both macroscopic and microscopic levels. In their study, they asked participants (children) to match their movement durations to those demonstrated by the researcher. The temporal organization of the movements and the pauses between them were at the participants' discretion. With this study, Manoel and Connolly were able to operationally define the macroscopic structure – i.e., the duration of the action as a whole – as well as the microscopic structure – i.e., the temporal organization of the movements – of the motor skill of interest.

Manoel and Connolly (1995) claimed that older children were able to vary aspects of the microstructure, such as the duration of movement components and their relative timing, while keeping the macrostructure, or overall duration, constant. Based on this observation, they argued that there the macrostructure and the microstructure constitute different levels of the hierarchically organized process of motor learning.

Golf putting has been modeled as a double-pendulum system composed of two arms and a club (Neal & Wilson, 1985). The shoulder is meant to roll in an up-and-down fashion, and the two hands hold the putter together, moving back-and-forth to putt symmetrically. However, the assumption that putting is a perfect pendulum movement requires careful consideration. Delay et al. (1997) found that, whereas novices showed the typical pendulum movement when putting, expert players did not (see also Neal, Abernethy, & Moran, 1990).

Previous research efforts have demonstrated that movement at impact was not decided upon at the moment of impact. Rather, the movement is planned, or attuned from initiation onwards (Bootsma & van Wieringen, 1988; Coello, Delay, Nougier, & Orliaguet, 2000; Frank, Weiker, & Robertson, 1985; Hubbard & Seng, 1954; Tydesley & Whiting, 1975), and through the period of swinging up to impact (Bootsma & van Wieringen, 1990; Müller & Abernethy, 2006; Savelsbergh et al., 1991). Furthermore, movement control might not be complete at impact (Delay et al., 1997).

The putting stroke comprises three phases: from initiation to top of back-swing (phase 1), from top of back-swing to impact (phase 2), and from impact to top of follow-through (phase 3). In the present study we examined how these phases differ between experts and novices.

To investigate differences and similarities between players of different levels of expertise in putting, this study placed specific constraints on the players: varying putter weight and goal distances. Putter weight and goal distances served as environmental/task constraints that both expert and novice players had to deal with during putting.

2. Methods

2.1. Participants

Five (5) expert and five (5) novice golfers volunteered to participate in the study. The five expert golfers included four males and one female, ranging in age from 19 to 46 years (mean = 32.4 years). All experts were teaching professionals and had single-digit handicaps (from 73 to 81 strokes). The five novice participants included four males and one female, with age ranging from 20 to 42 years

(mean = 30.6 years). All novices were students of Kunsan University, Korea, and had no golf-putting experience. No participant received any payment for his or her participation.

2.2. Materials and apparatus

Commercially available Xings putters (length: 80.3 cm, weight: 0.5 kg) were used in this study. A 250 g-lead weight was attached to the rear side of the club head using magnets for the weighted trials. To measure the putting movements, photographic markers were attached with adhesive tapes on top of the club head.

The moments of inertia of two putters, one with weight attached and one without weight were calculated by measuring the length and weight of each part of a club (grip, shaft, and head). The moments of inertia calculated for the light and heavy putters were 0.173 kg m and 0.298 kg m, respectively (for more detailed calculations, we refer to Kugler and Turvey (1987)).

Two video cameras captured movements at 60 frames/s, and APAS (Ariel Performance Analysis System) software was used to conduct three-dimensional motion analysis. The cameras were arranged in triangular formation, 5 m away from the participants (see Fig. 1). A $1 \times 1 \times 2$ m (x, y, z) reference frame was used for calibration. The experiment was conducted in an indoor putting room which has an artificial lawn.

2.3. Variables and study design

A coordinate system was defined for kinematic analysis with an x -axis (direction perpendicular to putting line), y -axis (direction of putting line), and z -axis (vertical direction).

Kinematic analyses were conducted on the following dependent variables: movement time, amplitude, velocity, and directionality. Expertise level, putter weight, and target distance were the independent variables. In order to examine the variability at the microscopic level, putting phase was also included as an independent variable in the analysis.

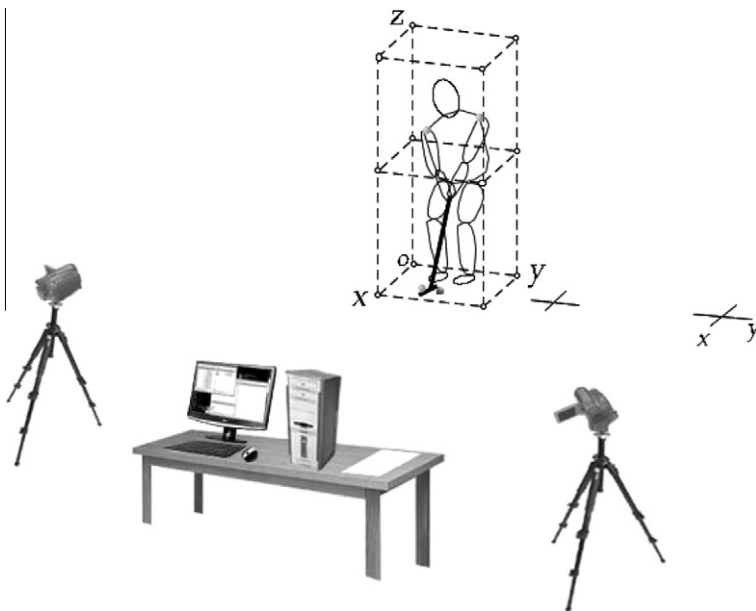


Fig. 1. Configurations of the experimental setting with two cameras, a computer, and a reference frame. Participants started to perform after the reference frame was removed from the setting.

The putter weight had two levels: the light putter weighted 500 g and the heavy putter weighted 750 g, due to the added 250 g-lead weight. There were three target distances: short (1.7 m), middle (3.25 m), and long (6 m). There were two levels of expertise: experts and novices. Data more than 3 SDs apart from the mean were considered outliers and excluded from the analysis.

“Error” was the variable representing the degree of (in)accuracy in golf putting. “Error” was calculated from the deviation of the position of the putted ball from target on the x - and y -axes, using the following formula:

$$\text{error} = \sqrt{(x' - x)^2 + (y' - y)^2}$$

where x' , y' denotes the position of the putted ball, and x , y denotes the position of the target.

A split-plot design involving one between-subject variable (group), and two within-subject variables (putter weight and distance) were used.

2.4. Procedure

When participants arrived for the study, each novice was instructed on how to put and was given between 5 and 10 min of practice. Each expert was allowed 5 min of practice. Each participant was then positioned in the putting area and began each trial on the instruction “ready, go” from the researcher. A ball was supplied at every trial. Before putting started for each target distance, participants were allowed five practice putts. Two weight levels and three distance levels within the block were randomly presented for each participant. The order of presentation of each condition was counterbalanced. Ten repetitions were conducted for each of the six conditions, resulting in a total of 60 trials.

The whole session was video recorded for kinematic analysis of each putter. In addition, to analyze accuracy, deviations of the putted ball from the target (i.e., on the x - and y -axes) were measured with a tape. Each participant took approximately 40 min to complete a session.

2.5. Data processing

The direct linear transformation (DLT) procedure was used to obtain three-dimensional (3D) coordinates for the three markers. The DLT routine initially involved calibration using 12 control points from the reference frame. The marker positions from the images of each camera were then digitized and finally 3D coordinates of the marker positions were calculated from two sets of digitized images of each scene. The DLT root mean squared error was 0.493 cm. Raw data were filtered by a Butterworth low-pass 2nd order digital filter with a cut-off frequency of 6.0 Hz to remove noise.

Five out of 10 trials (trials 4–8) for each condition were digitized and used in the analysis. Data from these five trials were averaged, and the analysis was performed on these averaged data. MATLAB (The MathWorks (Ver. 6.01), Natick, MA) and SPSS10 were used for data processing.

3. Results

3.1. Stroke duration

As shown in Table 1, there were some interactions of group with phase but minimal interactions among group, distance, and putter within a phase. An ANOVA was conducted on movement time with group, putter, and distance as independent variables for each phase. There was no interaction among the three dependent variables throughout the phases, but there was a significant main effect of distance, $F(2, 16) = 14.27$, $p < .01$, in phase 1, and putter $F(1, 8) = 7.38$, $p < .05$, in phase 2. A post-hoc test on distance in phase 1 revealed that the long-distance condition had different stroke duration from both the short and middle-distance conditions. All other effects were not significant, $p > .05$.

Another ANOVA was conducted on movement time with group, putter, distance, and phase as the independent variables, which yielded a significant Group \times Phase interaction, $F(2, 16) = 3.96$, $p < .05$. As can be appreciated from Fig. 2, this interaction revealed considerable differences between groups with regard to the relative timing for the three movement phases (for experts 0.863 s, 0.331 s, and

Table 1

Means and standard deviations of movement kinematics for experts and novices as a function of putter weight and goal distance for each phase.

Phase	Novice						Expert						
	Heavy			Light			Heavy			Light			
	Long	Middle	Short	Long	Middle	Short	Long	Middle	Short	Long	Middle	Short	
<i>Stroke duration (s)</i>													
1	M	0.886	0.861	0.792	0.847	0.824	0.765	0.934	0.885	0.829	0.885	0.839	0.804
	SD	(0.15)	(0.18)	(0.15)	(0.12)	(0.18)	(0.18)	(0.11)	(0.08)	(0.12)	(0.12)	(0.18)	(0.11)
2	M	0.387	0.403	0.407	0.361	0.380	0.378	0.344	0.329	0.319	0.329	0.316	0.323
	SD	(0.06)	(0.07)	(0.08)	(0.05)	(0.07)	(0.09)	(0.05)	(0.04)	(0.07)	(0.05)	(0.07)	(0.07)
3	M	0.449	0.495	0.455	0.449	0.468	0.442	0.640	0.679	0.697	0.685	0.669	0.704
	SD	(0.11)	(0.15)	(0.18)	(0.16)	(0.14)	(0.20)	(0.16)	(0.20)	(0.18)	(0.22)	(0.19)	(0.25)
<i>Stroke amplitude (m)</i>													
1	M	0.394	0.299	0.234	0.391	0.297	0.225	0.270	0.195	0.145	0.273	0.196	0.149
	SD	(0.06)	(0.05)	(0.04)	(0.04)	(0.05)	(0.05)	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)	(0.02)
2	M	0.395	0.299	0.235	0.390	0.298	0.226	0.267	0.192	0.146	0.272	0.195	0.151
	SD	(0.06)	(0.05)	(0.04)	(0.04)	(0.05)	(0.05)	(0.04)	(0.02)	(0.03)	(0.03)	(0.04)	(0.02)
3	M	0.459	0.348	0.246	0.450	0.367	0.257	0.532	0.461	0.347	0.551	0.455	0.338
	SD	(0.13)	(0.12)	(0.09)	(0.15)	(0.12)	(0.14)	(0.12)	(0.11)	(0.07)	(0.12)	(0.09)	(0.07)
<i>Stroke velocity (m/s)</i>													
1	M	-0.455	-0.359	-0.303	-0.471	-0.374	-0.301	-0.295	-0.221	-0.179	-0.315	-0.241	-0.190
	SD	(0.08)	(0.07)	(0.05)	(0.08)	(0.08)	(0.05)	(0.05)	(0.04)	(0.03)	(0.05)	(0.05)	(0.04)
2	M	1.024	0.742	0.569	1.083	0.785	0.598	0.764	0.587	0.461	0.835	0.625	0.480
	SD	(0.13)	(0.09)	(0.10)	(0.13)	(0.11)	(0.07)	(0.12)	(0.07)	(0.06)	(0.09)	(0.07)	(0.08)
3	M	1.034	0.716	0.556	1.036	0.790	0.578	0.881	0.703	0.518	0.851	0.706	0.521
	SD	(0.11)	(0.08)	(0.08)	(0.13)	(0.12)	(0.09)	(0.12)	(0.11)	(0.08)	(0.13)	(0.10)	(0.09)

0.675 s, for novices 0.829 s, 0.388 s, and 0.460 s in phase 1, phase 2, and phase 3, respectively). In comparison to novices, experts spent considerably more time in phase 1 and phase 3, but less time in phase 2.

The ANOVA showed a significant main effect of phase (0.846 s, 0.389 s, 0.537 s for phase 1, phase 2, and phase 3, respectively), $F(2, 16) = 49.11$, $p < .00$, but no main effects of group ($F(1, 8) = 1.20$, $p > .05$), distance ($F(2, 16) = 2.20$, $p > .05$), or putter ($F(1, 8) = 2.71$, $p > .05$).

3.2. Stroke time-to-peak velocity

Previous studies have identified the moment of contact as the most crucial event in the control of interceptive actions (Bootsma & van Wieringen, 1988; Frank et al., 1985; Hubbard & Seng, 1954; Tydesley & Whiting, 1975) and impact movements such as those involved in the game of golf (Pelz, 2000).

With this argument in mind, it appeared in examining the data that the time-to-impact (see Table 1 at phase 2) and the time-to-peak velocity (see Table 2) in both groups were very closely matched. Based on these observations, two ANOVAs were conducted on the variables time-to-impact (time from initiation to impact) and time-to-peak velocity (time from address to peak velocity), with group, distance, and weight as independent variables.

For time-to-impact, there was no main effect for group, $F(1, 48) < 1$, but significant main effects were found for distance, $F(2, 16) = 7.53$, $p < .01$, and weight, $F(1, 8) = 6.00$, $p < .05$. Similar results were found for time-to-peak velocity: there was no significant main effect for group, $F(1, 8) < 1$, but there were significant effects for distance, $F(2, 16) = 3.96$, $p < .05$, and weight, $F(1, 8) = 8.74$, $p < .05$.

There was a difference between experts and novices in terms of relative timing, i.e., in the instant at which peak velocity occurred during the down-swing (phases 2 and 3). In novices it occurred in the

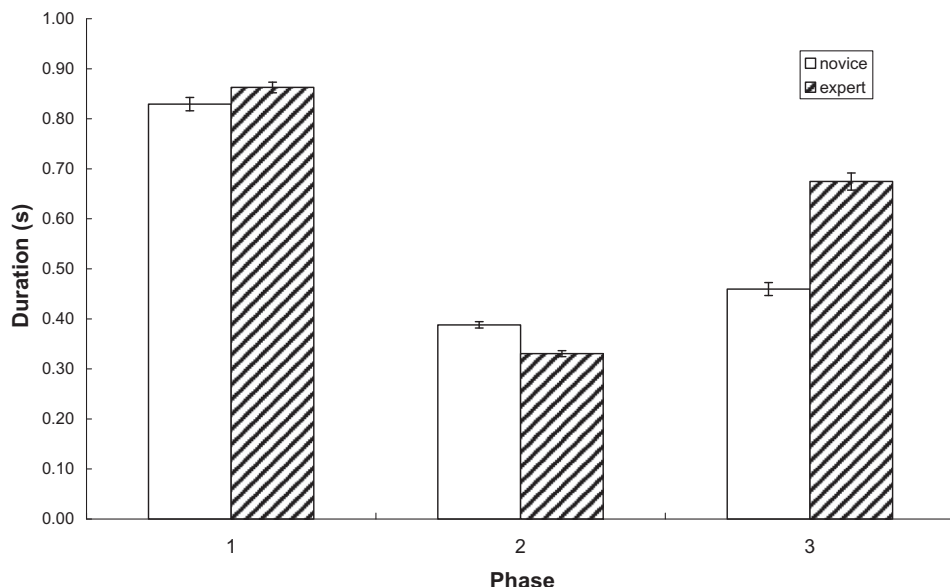


Fig. 2. Measurements of movement time for the two groups as a function of phase.

Table 2

Means and standard deviations of movement kinematics for experts and novices as a function of putter weight and goal distance at peak velocity.

	Novice						Expert					
	Heavy			Light			Heavy			Light		
	Long	Middle	Short	Long	Middle	Short	Long	Middle	Short	Long	Middle	Short
<i>Stroke duration (s)</i>												
M	1.274	1.267	1.217	1.208	1.209	1.151	1.297	1.293	1.215	1.223	1.204	1.164
SD	(0.21)	(0.25)	(0.25)	(0.16)	(0.24)	(0.32)	(0.13)	(0.11)	(0.17)	(0.16)	(0.23)	(0.17)
<i>Stroke amplitude (m)</i>												
M	0.400	0.301	0.242	0.386	0.305	0.233	0.301	0.289	0.209	0.286	0.259	0.185
SD	(0.08)	(0.09)	(0.07)	(0.08)	(0.09)	(0.10)	(0.05)	(0.09)	(0.06)	(0.08)	(0.09)	(0.05)
<i>Stroke velocity (m/s)</i>												
M	1.936	1.402	1.093	2.021	1.538	1.143	1.811	1.351	1.034	1.899	1.418	1.052
SD	(0.16)	(0.13)	(0.12)	(0.16)	(0.16)	(0.13)	(0.11)	(0.10)	(0.07)	(0.11)	(0.09)	(0.06)

middle of the down-swing, but in experts it occurred much earlier (0.374 vs. 0.472 for experts and novices, respectively), $F(1, 8) = 6.34, p < .05$. Novices displayed symmetrical patterns, whereas experts showed asymmetrical, variant patterns with regard to the duration of peak velocity (see also Delay et al., 1997).

3.3. Stroke amplitude

An ANOVA was conducted on amplitude with group, putter, and distance as independent variables. There was no interaction between independent variables. In phase 1, there were significant main effects of group, $F(1, 8) = 37.83, p < .00$, and distance, $F(2, 16) = 178.36, p < .00$, but no effect of putter, $F(1, 8) < 1$.

Post-hoc *t*-tests showed that all three distance conditions were different. The amplitude of the putt increased with increasing goal distance (see Table 1).

In phase 2, as in phase 1, the effect of group was significant, $F(1, 8) = 39.41, p < .00$, as was distance, $F(2, 16) = 154.51, p < .00$, but the effect of putter was not, $F(1, 8) < 1$. Post-hoc analysis for distance

showed that all three distances were different from each other (0.331 m, 0.248 m, and 0.190 m, for long, middle, and short distances, respectively). In phase 3, distance was significant, $F(2, 16) = 71.85$, $p < .00$, but group, $F(1, 8) = 1.87$, $p > .05$, and putter, $F(1, 8) < 1$, were not.

A detailed ANOVA was conducted on amplitude with group, putter, distance, and phase as independent variables. As shown in Fig. 3, there was a significant Group \times Phase interaction, $F(2, 16) = 7.74$, $p < .01$; therefore, ANOVAs were conducted on each phase separately. There were significant effects by group in phase 1, $F(1, 8) = 39.41$, $p < .01$, and in phase 2, $F(1, 8) = 38.81$, $p < .01$, but not in phase 3, $F(1, 8) = 1.87$, $p > .05$. In phases 1 and 2, experts showed smaller amplitudes than novices, but in phase 3 experts showed larger amplitudes than novices, although this trend did not reach significance.

3.4. Stroke amplitude at peak velocity

We analyzed the relative amplitude of peak velocity (from top of back-swing to peak velocity) within the down-swing (phases 2 and 3). For novices this point occurred at approximately the middle of the down-swing, but for experts it occurred far before mid-down-swing (0.374 vs. 0.472, for experts and novices, respectively) (see Table 2), $F(1, 8) = 27.27$, $p < .00$, consistent with the result reported by Delay et al. (1997).

Fig. 4 revealed that differences existed in the movement trajectories of both groups. Novices showed a more convoluted and variable movement trajectory than experts. In contrast to the novices' symmetrical trajectory with respect to point of impact (vertical line at zero in Fig. 4), the experts' trajectory was asymmetrical in that the length of the post-impact trajectory was much longer than the pre-impact trajectory (see Fig. 4A). Furthermore, the movement trajectory of experts was curvilinear while that of novices was planar. This outcome, however, appears to contradict observations by Delay et al. (1997) that experts had planar trajectories while novices had curvilinear trajectories.

3.5. Stroke velocity

Table 1 shows that experts had lower velocity than novices. An ANOVA was conducted on club velocity with group, putter, and distance as independent variables. In phase 1, there was no interaction.

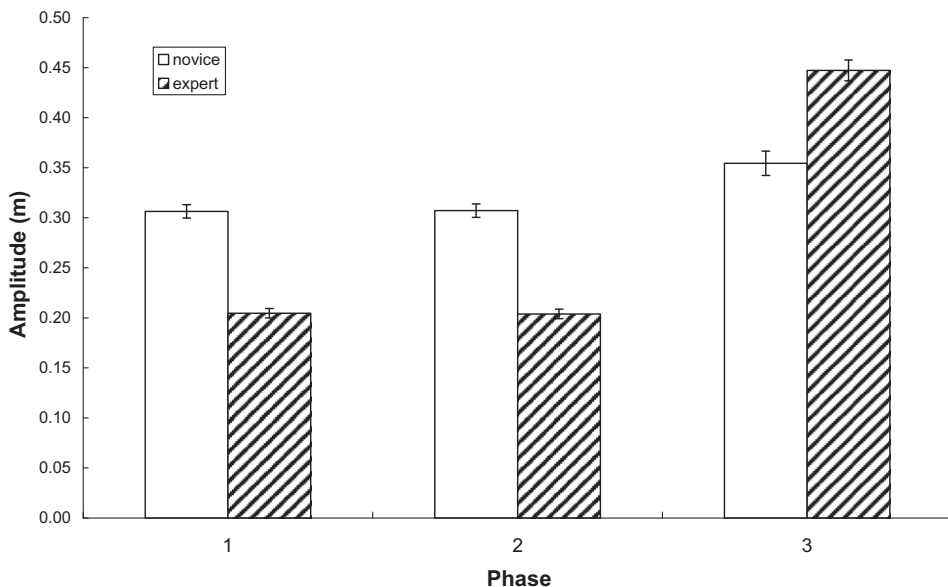


Fig. 3. Measurements of amplitude for the two groups as a function of phase.

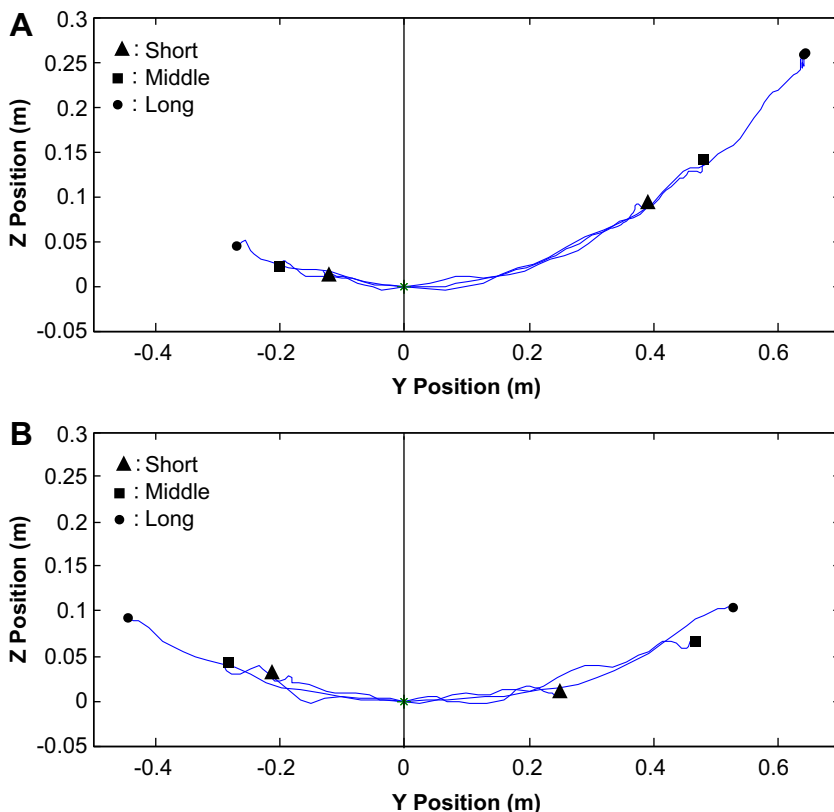


Fig. 4. Movement trajectories for phases 2 and 3 (down-swing), for one participant from each group, using a light putter (experts (A) and novices (B)).

The effect of group was significant, $F(1, 8) = 21.39$, $p < .05$, as was that of distance, $F(2, 16) = 757.89$, $p < .00$, but, there was no effect of putter, $F(1, 8) = 3.71$, $p > .05$. In phase 2, there was a significant Group \times Distance interaction, $F(2, 16) = 11.43$, $p < .01$. Nevertheless, the trend showed that novices had the higher velocity for all three distances. There were significant effects of group, $F(1, 8) = 25.40$, $p < .01$, distance, $F(2, 16) = 355.42$, $p < .00$, and putter, $F(1, 8) = 10.56$, $p < .05$.

In phase 3, there was a significant Group \times Distance interaction, $F(2, 16) = 13.83$, $p < .01$. As was the case in phase 2, novices exhibited the higher velocity for all three distance conditions. There was a significant main effect of group, $F(1, 8) = 7.98$, $p < .05$, and distance, $F(2, 16) = 486.72$, $p < .00$, but, no effect of putter, $F(1, 8) < 1$.

Another ANOVA was conducted on club velocity with group, putter, distance, and phase as independent variables. The results showed a significant Group \times Distance interaction, $F(2, 16) = 21.08$, $p < .00$. Differences in velocity between experts and novices were greatest for long-distance targets and smallest for short-distance targets. There was also a significant three-way interaction between group, distance, and phase, $F(4, 32) = 3.52$, $p < .05$. Novices showed more divergence with distance than did experts as the phase progressed.

Also, we observed significant main effects of group, $F(1, 8) = 33.90$, $p < .00$ (0.625 m/s vs. 0.800 m/s for experts and novices, respectively), distance, $F(2, 16) = 757.89$, $p < .00$ (0.927 m/s, 0.685 m/s, and 0.527 m/s for long, middle, and short distances, respectively), and phase, $F(2, 16) = 316.52$, $p < .00$, but no effect of putter, $F(1, 8) = 3.17$, $p > 0.05$.

There was a significant difference between groups: experts had lower velocity than novices across all three phases (see Fig. 5). In addition, there was an effect of goal distance: velocity was higher for long-distance targets than for short-distance targets.

3.6. Stroke velocity at peak velocity and at impact

An ANOVA on velocity at peak velocity was conducted, which revealed significant main effects of group, $F(1, 8) = 11.05$, $p < .5$ (1.426 m/s vs. 1.522 m/s, for experts and novices, respectively), putter, $F(1, 8) = 16.51$, $p < .05$, and distance, $F(2, 16) = 685.04$, $p < .00$. A separate ANOVA on velocity at impact was also conducted, which revealed significant main effects of group, $F(1, 8) = 8.25$, $p < .05$ (1.295 m/s vs. 1.433 m/s, for experts and novices, respectively), putter, $F(1, 8) = 6.68$, $p < .05$, and distance, $F(2, 16) = 85.50$, $p < .00$.

These results indicated that velocity at peak velocity and velocity at impact are the variables that exhibited the highest sensitivity to the constraints imposed by club weight and goal distance, as a function of level of expertise. Also, velocity at peak velocity was even more sensitive to these task constraints than velocity at impact.

3.7. Accuracy of putting

An ANOVA was conducted to assess accuracy variability using “Error” as the dependent variable, with group, putter, and distance as independent variables. There were significant main effects of group, $F(1, 8) = 32.41$, $p < .00$, and distance, $F(2, 16) = 15.10$, $p < .00$, but no effect of putter, $F(1, 8) < 1$. Experts were more accurate than novices and increased target distance was associated with reduced accuracy (see Fig. 6).

3.8. Directional variability

Variability in directionality was measured by the deviation of putter trajectory along the x -axis, which is the direction perpendicular to the putting line. Separate ANOVAs were conducted on directional variability for each phase.

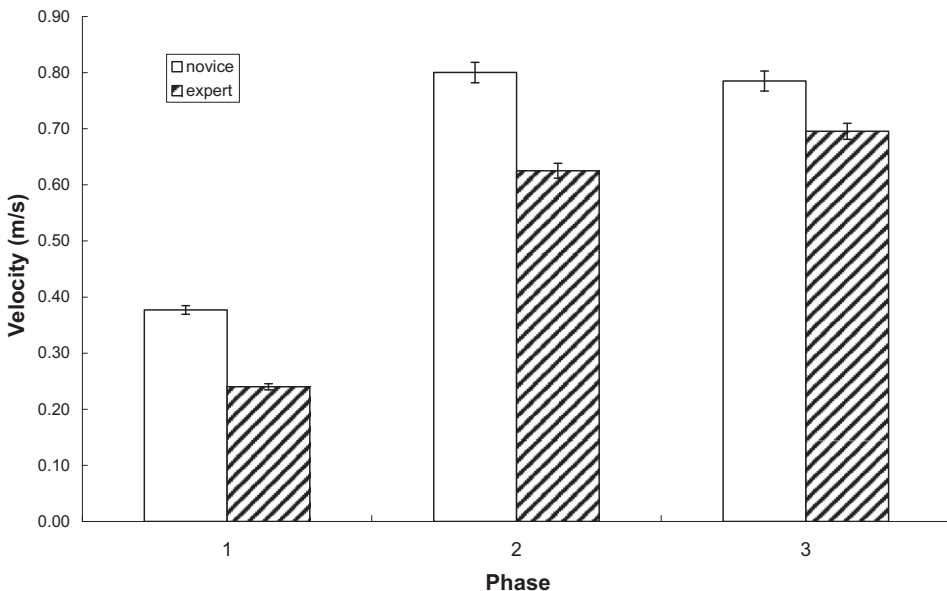


Fig. 5. Velocity for the two groups as a function phase.

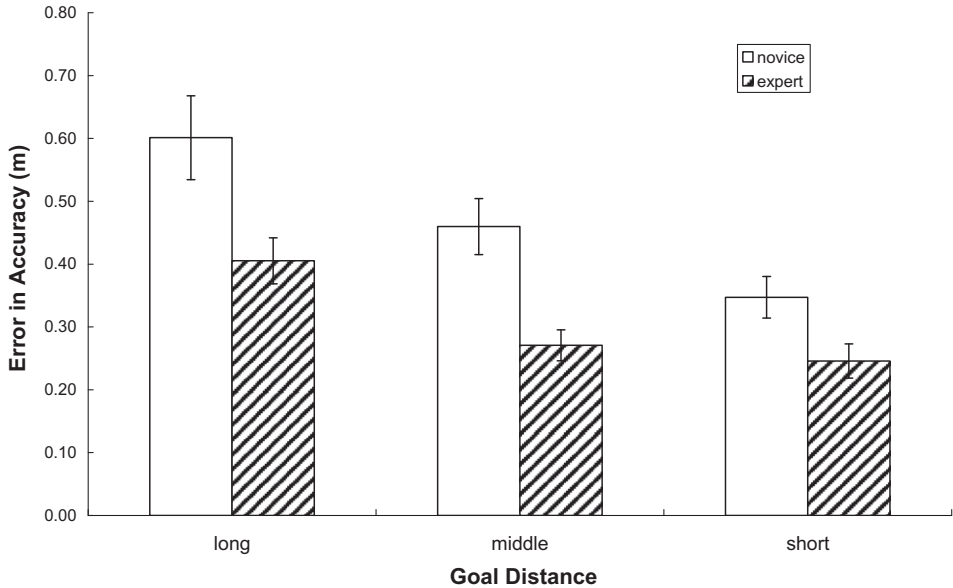


Fig. 6. Variability in accuracy for the two groups as a function of three goal distance conditions.

In phase 1 (see Fig. 7), there were significant main effects of group, $F(1, 8) = 17.73, p < 0.005$, and distance, $F(2, 16) = 7.15, p < .01$, but no effect of putter, $F(1, 8) < 1$. Experts exhibited less variability than novices. With regard to goal distances, short distance was associated with significantly lower variability than middle distance, but there was no difference between the middle and long distances.

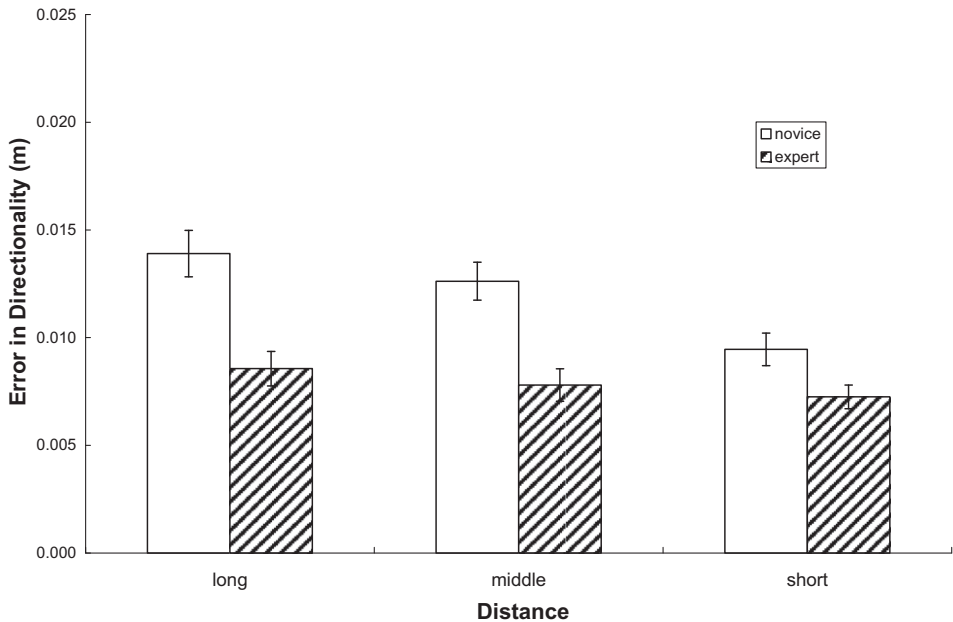


Fig. 7. Directional variability of putting movement for the two groups as a function of distance; phase 1.

In phase 2 (see Fig. 8), there was a significant Distance \times Group interaction, $F(1, 8) = 4.26, p < .05$. Experts tended to show the greatest variability for the long distance and the least variability for the short distance. Interestingly, novices showed much higher variability for the middle distance as com-

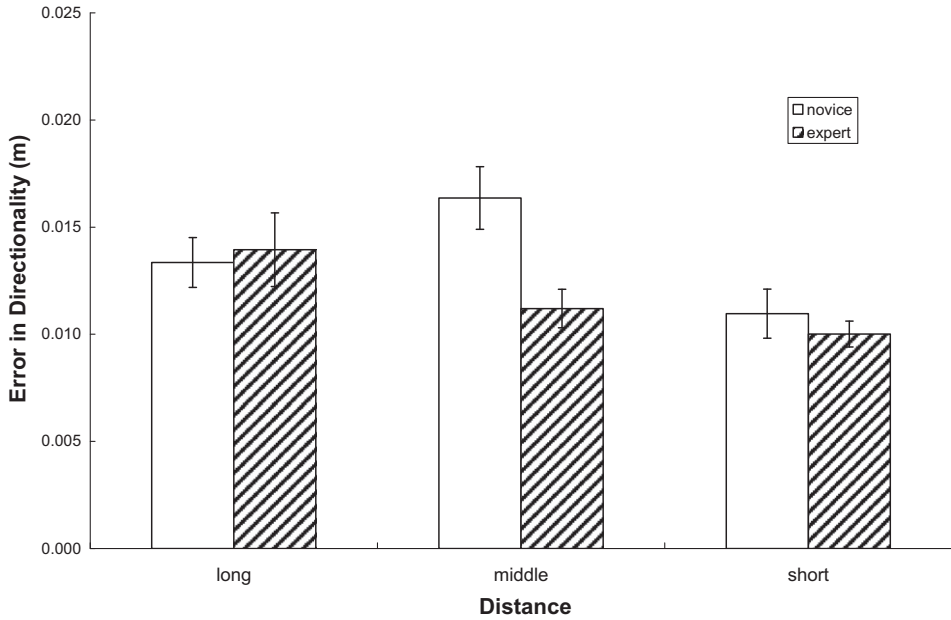


Fig. 8. Directional variability of putting movement for the two groups as a function of distance; phase 2.

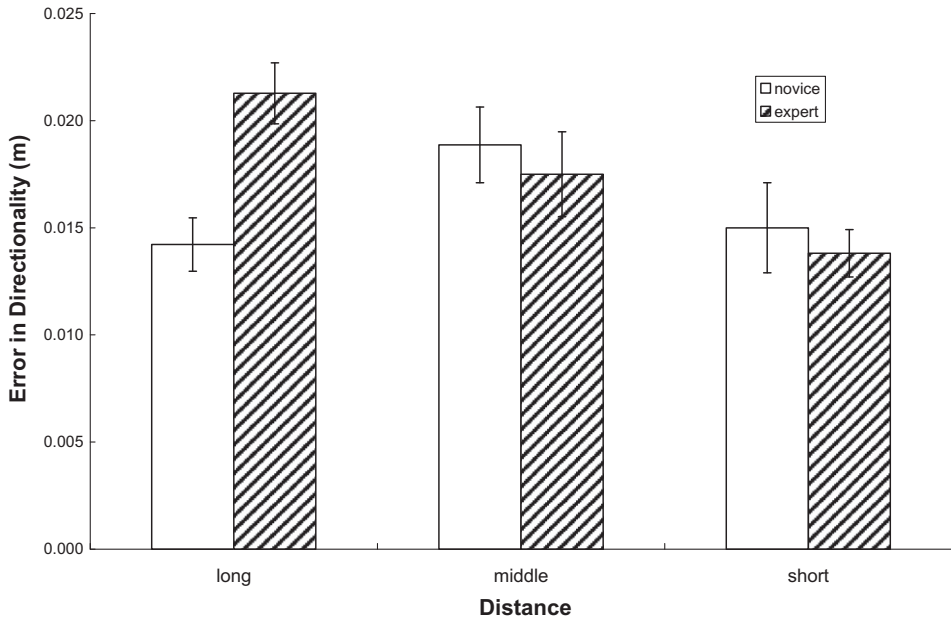


Fig. 9. Directional variability of putting movement for the two groups as a function of distance; phase 3.

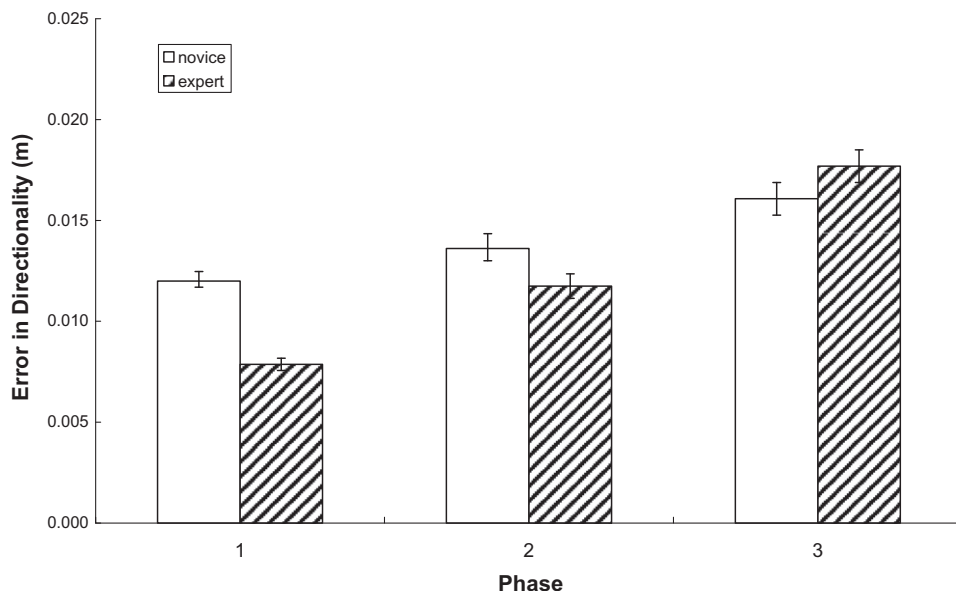


Fig. 10. Directional variability of putting movement for the two groups as a function of phase.

pared to the other distances. There was a significant main effect of distance, $F(2, 16) = 6.72, p < 0.01$, but no significant effects of group, $F(1, 8) = 2.95, p > .05$, and putter, $F(1, 8) = 3.71, p > .05$. Variability was lower for the short distance than the middle distance, and there was no difference between long and middle goal distances.

In phase 3 (see Fig. 9), there was a significant Distance \times Group interaction, $F(2, 16) = 3.77, p < .05$. As observed in phase 2, experts showed the highest variability for the long distance, and novices showed the highest variability for the middle-distance condition. There was no main effect of group, $F(1, 8) < 1$.

A more detailed ANOVA was performed to measure directional deviations from the x -axis with distance, putter, group, and phase as independent variables. The data showed a two-way interaction between phase and group, $F(2, 16) = 4.54, p < .05$. As shown in Fig. 10, in phases 1 and 2 experts had lower variability than novices, but in phase 3 experts showed higher variability. There was also a three-way interaction between phase, distance, and group, $F(4, 32) = 4.90, p < .01$. Furthermore, there were significant main effects of phase, $F(2, 16) = 27.11, p < .00$, and distance, $F(2, 16) = 6.83, p < .01$, but no significant effects of group, $F(1, 8) = 3.03, p > .05$, and putter, $F(1, 8) < 1$.

4. Discussion

4.1. Macroscopic vs. microscopic levels of task organization

Our results revealed that time-to-impact and time-to-peak velocity did not distinguish experts from novices. For both groups of participants these measures were invariant over putting distance and putter weight. The results showed that time-to-impact and time-to-peak velocities were unaffected by the level of expertise, and suggested that these parameters are fundamental to movement control in golf putting (see also Rinkenauer, Ulrich, & Wing, 2001).

However, at the micro-level of each phase, there were marked variations in timing between the two groups: movement times of experts were longer in phase 1 (0.863 s vs. 0.829 s for experts and novices), shorter in phase 2 (0.331 s vs. 0.388 s), and longer again in phase 3 (0.675 s vs. 0.460 s).

The results showed that expert and novice players modified the duration of each phase differently, and that the relative timing differed between groups.

The same trend was found for stroke amplitude. Whereas stroke amplitude from start to finish of the down-swing was symmetrical about the ball's ground position ($y = 0$) for novices (Fig. 4B), it was asymmetrical for experts (Fig. 4A).

These results can be interpreted from Manoel and Connolly's (1995) and Manoel et al.'s (2002) perspective that motor learning is a hierarchical process consisting of macroscopic and microscopic levels. The consistency at the macroscopic level, which was demonstrated by the invariance of timing at impact, appeared to be achieved by variations at the microscopic level, evidenced by differences in relative timings and relative amplitudes between the two groups.

Conversely, the outcome did not confirm the invariant relative timing hypothesis derived from the theory of generalized motor programs (Schmidt et al., 1976, 1985), which posits that the ratios of time spent in the component phases are fixed.

It appeared that skill learning modulation is based on the principle that some fundamental property remains unchanged while other properties are allowed to vary depending on the level of expertise (Manoel & Connolly, 1995; Manoel et al., 2002) and the prevailing constraints (Schmidt et al., 1979). That is, the organization of motor learning is not just a single-layer process, as proposed by the impulse variability model (Schmidt et al., 1979), but rather a hierarchical process organized at both macroscopic and microscopic levels.

4.2. Velocity at impact

The impulse variability model (Schmidt et al., 1979) predicts that to reach any target at a given distance, the velocity at impact should be similar in both groups. The results of the present study provided no support for this hypothesis. Compared to novices, experts showed reduced movement velocity and improved accuracy.

The experts' choice of a lower level of velocity was excellent, since they achieved higher accuracy, and thus used their energy more efficiently than novices, but it raised the question as to how they succeeded in reaching the target at this lower velocity. Delay et al. (1997) reported the same results in their study. In explaining their results, the authors suggested that the energy produced by novices might not be entirely transferred to the ball. In other words, at the moment of contact there is a greater energy loss in novices than in the expert players.

The findings in this study lend support to this claim. Our data showed that peak velocity of the expert group occurred after impact, which means the ball gained an even stronger impulse when it left the club than at the moment of impact. The movements of the expert players continued to accelerate during and immediately after impact; hence loss of energy at impact was less in expert players than in novices.

A second explanation provided by Delay et al. (1997) was that greater loss of energy occurred when the ball was traveling after being hit by novices as compared with experts; they observed that balls delivered by novices often bounced, whereas the experts' balls glided smoothly over the green. Delay et al. (1997) suggested that the velocity discrepancy between the two groups at impact was caused by different orientations of the club head in contact with the ball (see also Karlson, Smith, and Nilsson (2008)).

We have a different explanation than that provided by Delay et al. (1997). We suggest that expert players achieved greater energy efficiency by striking the ball in such a way that it rolls rather than slides towards the target. A ball loses less kinetic energy when it rolls compared to when it slides. Therefore, when the ball rolls, it can travel the same distance with less impulse or lower impact velocity. Also, when rolling, the friction is more consistent, rendering the trajectory of the ball more predictable and controllable. We suggest that because of the rolling, energy loss was much less for the experts; therefore experts were able to reach the target with a smaller amount of force and less movement velocity. We also suggest that rolling occurred because the experts hit the ball with the club during the upward, rising phase of swing, when the velocity of the club head was still increasing. Notably, experts hit the ball with the putter when the putter had just passed the lowest point of its trajectory and the club head was elevated slightly upward at about 2–3 mm in the air (Pelz, 2000).

4.3. Variability in directionality

The analysis of variability on the x-axis, which was the measure of deviation in directionality, showed that there was a three-way interaction among group, phase, and distance. The data demonstrated that in phase 1 (see Fig. 7), both experts and novices showed linear increments of directional variability as the goal distance increased, and experts displayed lower variability than novices for all three distances. The results suggested that in phase 1 the direction of movement was maintained better by the experts, and was more simple and noiseless than that of the novices. Experts appeared to move in a mechanical fashion, whereas novices appeared to make repeated adjustments and corrections to their movement during the back-swing. There was no difference between groups in phase 2, but in phase 3 experts showed more variability than novices.

However, the groups exhibited quite different patterns with respect to distance in phase 2 (see Fig. 8) and phase 3 (see Fig. 9). For experts directional variability was the highest for the long-distance condition, and the lowest for the short-distance condition. In other words, there was a linear correlation between distance and directional variability. However, results showed a different pattern for novices: the middle-distance condition exhibited the highest directional variability, whereas short- and long-distance conditions showed a lower level of variability, thereby showing a hyperbolic pattern. It seems that for the long-distance condition, which was the most difficult condition, experts took a more flexible movement path, whereas novices took a more stringent movement path (during phases 2 and 3).

Even though the directional variability of experts as compared with novices was much higher during phases 2 and 3 for the long-distance condition, the results showed that experts were more accurate than novices in the long-distance condition. In inspecting both sets of results, a tentative explanation is that, at least, for the long-distance condition of phase 3, the directional variability of putter path did not play a primary role in achieving accurate putting. This result is consistent with the work of Karlson et al. (2008), who claimed that face angle had a greater effect on directional accuracy in putting than putter path or impact point.

The long follow-through, which might have been necessary for the experts' accuracy in the long-distance condition, may have created the high directional variability for the experts. Novices' lower variability in the long-distance condition could be explained by Bernstein's notion of degrees of freedom (Bernstein, 1967; Turvey, Fitch, & Tuller, 1982). Encountering the long-distance condition, and having no experience with putting, novices might not know how to control so many degrees of freedom of their body parts, and therefore used only a limited number of their body parts during putting, as robots do, resulting in low directional variability.

4.4. Importance of BS amplitude

Optimal velocity at impact is crucial for accurate putting (Delay et al., 1997). In order to achieve the optimal velocity, it is necessary to control the amplitude and/or duration of movement during phase 2. Across both experts and novices, duration of movement in phase 2 was not significantly different for the three distance conditions. This implies that significantly different velocities for the three different goal distances in phase 2 were achieved through different movement amplitudes in phase 2. Since movement amplitudes in phase 2 were always identical to those in phase 1, we conclude that differences in velocity in phase 2 must have arisen from phase 1.

It can, therefore, be hypothesized that the amplitudes in phase 1 were crucial for the velocity at impact, which, in turn, determines the accuracy of putting (also refer to Delay et al., 1997). A finding of interest was that amplitudes in phase 1 were shorter for experts than for novices: 0.205 m vs. 0.307 m for experts and novices, respectively.

The cause of the higher variability of experts as compared to novices for the long-distance condition, as well as the higher variability for novices in the middle-distance condition as compared to both the long- and short-distance conditions, remains to be elucidated. Future research efforts may help to resolve this interesting question.

Also, this study included only one putting session to study putting in golfers of different skill levels. We did not examine how movement variability changes with practice and how novices progress in

becoming more skilled. Future studies investigating this issue will help to enhance our understanding of motor learning.

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