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Movement control in golf putting

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Abstract

The purpose of the study was to understand how force is controlled for impact movements such as golf putting. Expert players (10) and control subjects (10) executed a putt as accurately as possible, in order to reach a target distance of 1, 2, 3, or 4 m. Movements of the club were recorded at 200 Hz via a SELSPOT system. Overall, the results showed that, in order to increase club velocity at the moment of contact with the ball with increasing distance of the target, subjects increased the downswing (DS) amplitude maintaining DS movement time constant. The change in force required to reach the different distances seemed to rely on an adjustment of the magnitude of the motor command within the same time period. Furthermore, our results showed that the movement of putting consists primarily in specifying the amplitude of the Backswing (BS) as a function of the distance of the target. This gives rise to a motor impulse originating the force–time function required for an adequate DS movement. © 1997 Elsevier Science B.V.

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1. Introduction

One of the problems to be solved in movement execution is to define the muscular force necessary for moving the limb and/or the body in space. Many authors have investigated this question by manipulating the intensity of the force required for executing the same task. The increase in muscular force applied to the limb for performing a task depends on the mass of the segment and on the acceleration applied to it. In summary, an increased force output can be obtained by (1) increasing movement amplitude and keeping movement time constant (e.g., Schmidt et al., 1978; Newell et al., 1979; Wallace and Wright, 1982; Carlton et al., 1983; Gielen et al., 1985; Shapiro and Walter, 1986; Temprado et al., 1994); (2) maintaining movement amplitude constant and decreasing movement time (e.g., Newell et al., 1980; Soechting and Lacquaniti, 1981; Zelaznik et al., 1986; Schmidt et al., 1988; Wallace and Weeks, 1988; Wallace and Kelso, 1990; Teasdale and Schmidt, 1991; Teulings and Schomaker, 1993; Wright, 1993); or (3) adding an unexpected load on the limb to be moved while maintaining movement amplitude and movement time constant (e.g., Schmidt et al., 1980; Schmidt et al., 1986; Lacquaniti et al., 1982; Newell et al., 1982; Sherwood et al., 1988).

Accordingly, in order to produce different amplitudes, the parameters of the movement which have to be scaled are amplitude and duration (Schmidt et al., 1979; Meyer et al., 1982). In other words, the control of the movement requires a specification of force over time. To account for such control, a general notion of scaling – the prototype function model – has been proposed by Meyer et al. (1982) and reformulated later by Ulrich et al. (1995). The basic idea is that multiplicative scaling factors for the amplitude and duration of the force are specified during motor programming in order to adapt the memorized prototypical force–time function to the new environmental constraints. The underlying assumption is that force and/or duration parameters of a given function can be scaled to each other without affecting the mathematical form of the function. It is worth noting that this force–time function can be related to the so-called “impulse-timing” theory of Schmidt et al. (1978, 1979) which hypothesizes that a motor program specifies the pattern of temporal force produced by the muscles, and is thus responsible for the trajectory (i.e., the path) ensured by the limb.

Studies on arm movement have described the action of active and reactive torques at joint level putting forward the absence of a clear equivalence between motor impulse and movement kinematics (Hollerbach and Flash, 1982). As a consequence, numerous studies focused on the control of isometric force impulse, arguing that no convincing evidence could emerge from a behavioral (kinematic) analysis to support the idea that the central nervous system uses scaling (see Ulrich et al., 1995 for a review). With regard to the isometric force control paradigm, most of the results agreed that, in order to reach forces of different intensities, the control system refers to a scaling of force amplitude with minor changes in overall duration (Freund and Büdingen, 1978; Ghez and Vicario, 1978; Carlton et al., 1987; Corcos et al., 1990). These results engendered several modelisation attempts, as e.g. the pulse height control model (Gordon and Ghez, 1987), or the parallel force unit model (Ulrich and Wing, 1991, 1993). According to the latter, force is controlled either by specifying the number of recruited force units or by defining how long each force unit contributes to the production of force. The model predicts an amplitude scaling with a similar invariant shape of the force–time function if peak force is controlled by the recruitment of force units. Conversely, the model predicts a change in the shape of the force–time function if force control is based on the specification of force units duration violating the prototype function model (see above). Recent investigations supported this model demonstrating that both amplitude and duration of force can be adjusted according to the task constraints (Ulrich et al., 1995).

Providing indirect evidence, the kinematic analysis of the movement has also been used in order to understand the time–amplitude scaling better. Results obtained with grasping or pointing movements confirmed the conclusions of the isometric control of force studies. Changes in movement amplitude induced a modulation of peak force while maintaining the duration of force recruitment constant. For example, Jeannerod (1984) reported that in order to reach objects at different amplitudes, peak velocity of the movement increased with no effect on movement duration. Similarly, in a study investigating the control of eye movements, Abrams et al. (1989) observed that acceleration waveforms were superimposable after monotonic transformations on the amplitude and time axes. Complex learned movements seem to be controlled on the basis of similar functional rules. Indeed, the same pattern of results was observed in tasks as varied as drawing (Denier von der Gon and Thüring, 1965; Decety et al., 1989), handwriting (Viviani and McCollum, 1983), or typing (Viviani and Terzuolo, 1983).

The purpose of the present experiment was to understand better how the force and amplitude of the movement are controlled in the case of impact movements (e.g., the snooker, or the penalty situation in hockey or soccer). More specifically, we investigated the movement of putting in golf (i.e., the last drive when the ball is on the green) for different distances from the hole. The aim of this movement is to impart, with a club, a given force to an immobile ball in order to put it into the hole (i.e., to travel the distance between the ball and the hole). For this kind of movement, no movement time and movement amplitude are imposed to the player. The main external constraint is that the ball must fall in a hole located at varying distances. This implies a variation of the force applied by the club to the ball at the moment of contact. In many motor skills, namely those with no velocity constraints, movement adjustments are frequently present during the entire movement until the goal is reached (e.g., pointing and grasping movements). In golf putting, as in all impact movements, the subject cannot control the ball once it has been hit, whereas the purpose of the task is still not achieved. In other words, it is not clear whether movement control ends on contact with the ball or is prolonged until the end of the movement (i.e., the contact with the ball is a specific event included in a larger movement).

In order to investigate better how subjects controlled the force applied to the ball, we compared control subjects to expert players. The environmental constraints were the same for all subjects and theoretically required the same force output to reach the target. It is possible, however, that expert players learnt to specify movement force in a different way.

2. Methods

2.1. Subjects

Ten golf players (three females and seven males, mean age 23) and 10 control subjects having no golf experience (three females and seven males, mean age 26) participated in the study. The expert players were professionals or had a handicap lower than five. All subjects gave their informed consent.

2.2. Apparatus and task

A 5 m long and 75 cm wide piece of wood simulated a golf green. It was covered by a carpeted surface the texture of which reproduced quite well the texture of a real green. The coefficient of friction of the surface was 0.69. Circles of 5 cm diameter and a distance of 1, 2, 3, and 4 m from the starting position of the ball were drawn on the green and served as targets. The subject's task was to perform a putt as accurately as possible in order to reach the requested target.

2.3. Data recording

Movements of the head of the club were bi-dimensionally recorded at 200 Hz via a SELSPOT system (12 bits A/D converter). The spatial accuracy of the recordings was ±2 mm. The camera was placed in front of the subject at a distance of 2.5 m. One infra-red emitting diode was fixed on the lower part of the club. After collection, data were filtered with a second-order Butterworth filter with dual-pass to remove phase shift (8 Hz cut-off frequency). Position–time traces were then differentiated to obtain velocity profiles.

To estimate when the impact of the club with the ball occurred during the execution of the movement, the ball was put onto a contactor which was inserted in the simulated green. When the ball was hit, the contactor was released.

2.4. Procedure

Prior to the experiment, each subject performed a series of training trials (approximately five trials for each distance). For a given trial, the experimenter first indicated the target to be reached. Then, the subject adjusted her/his feet and posture in order to execute the putt comfortably and indicated when she/he was ready. Subjects were free to define the initial position of the club. The sampling time was initiated by a 1-s sound signal. Then, the subject had 5 s for executing the movement. Subjects were instructed to be as accurate as possible. A trial was considered to be successful when the ball stopped on a zone centered on the target and having a diameter corresponding to 5% of the distance to be covered (i.e., the diameter of the zone of accuracy was 5, 10, 15 and 20 cm, for the 1, 2, 3, and 4 m distances, respectively). This procedure allowed us to maintain movement accuracy proportionally constant from one distance to another. The trials for the four distances were randomized. The experiment ended when 10 correct trials for each distance were recorded (i.e., 40 trials in all). Control subjects performed the task with the same club, whereas the expert players used their own club in order to limit the possible perturbations induced by the experimental set-up.

Table 1
The mean, standard deviation and coefficient of variability for each dependent variable for the two groups and the four distances. Data in brackets are those of the pendulum

	1 m			2 m			3 m			4 m		
	Mean	SD	%SD	Mean	SD	%SD	Mean	SD	%SD	Mean	SD	%SD
Novice players												
Spatial features (mm)												
BS amplitude	142	26	19	202	26	13	257	27	11	306	27	9
DS amplitude	326	52	16	486	59	12	607	71	11	717	63	9
Amplitude to impact	164 (278)	31	18	222 (397)	30	14	272 (461)	33	12	325 (532)	39	12
Amplitude from impact to DS end	162	35	21	264	48	16	335	60	17	392	51	12
Amplitude to pic velocity	156	36	22	235	46	19	294	53	17	352	62	17
Amplitude from pic velocity to DS end	170	32	19	252	41	16	313	53	17	369	56	15
Amplitude from the ball at the beginning of the BS	21	16	35	18	14	46	20	16	53	15	13	63
Temporal features (ms)												
BS movement time	417	42	10	482	36	8	512	43	9	532	40	8
DS movement time	527	65	12	565	50	9	577	60	10	584	48	8
Time to impact	264 (408)	34	13	267 (419)	25	10	269 (419)	23	9	273 (426)	23	9
Time to pic velocity	255	30	13	274	50	13	279	49	11	285	48	11
Time from pic velocity to DS end	272	48	17	291	77	15	298	73	14	299	77	14
Kinematics features (m-s-1)												
Velocity to impact	0.62 (0.63)	0.049	8	0.83 (0.85)	0.05	6	1.01 (1.02)	0.055	5	1.18 (1.15)	0.079	7
Velocity to pic velocity	0.62	0.052	9	0.86	0.07	8	1.05	0.08	8	1.23	0.103	8
DS velocity	0.62	0.04	7	0.86	0.056	7	1.05	0.091	9	1.24	0.094	8
Velocity at impact	0.93	0.032	3	1.34	0.028	3	1.69	0.017	3	2.05	0.018	3

Expert players												
Spatial features (mm)												
BS amplitude	134	7	5	199	8	4	242	7	3	288	9	3
DS amplitude	388	23	6	611	39	6	772	56	7	917	63	7
Amplitude to impact	137	8	6	196	9	5	233	9	4	275	11	4
Amplitude from impact to DS end	252	23	9	415	39	9	539	56	10	642	64	10
Amplitude to pic velocity	180	16	9	302	28	9	386	35	9	459	31	7
Amplitude from pic velocity to DS end	208	27	13	309	40	12	386	56	14	458	59	13
Amplitude from the ball at the beginning of the BS	6	3	76	7	3	63	7	4	69	12	6	52
Temporal features (ms)												
BS movement time	498	22	4	573	21	4	614	26	4	650	20	3
DS movement time	665	40	6	732	38	5	721	34	5	719	32	5
Time to impact	261	14	6	281	12	4	283	12	4	289	10	4
Time to pic velocity	310	105	37	356	9	7	364	109	5	361	100	4
Time from pic velocity to DS end	355	106	12	377	73	11	358	83	10	359	95	9
Kinematics features (m-s-1)												
Velocity to impact	0.52	0.023	4	0.70	0.034	5	0.83	0.032	4	0.97	0.04	4
Velocity to pic velocity	0.58	0.032	6	0.85	0.053	7	1.06	0.064	6	1.27	0.069	6
DS velocity	0.58	0.029	5	0.82	0.054	6	1.04	0.064	6	1.25	0.076	6
Velocity at impact	0.85	0.022	3	1.22	0.036	3	1.52	0.038	3	1.83	0.05	53

It should be noticed that the experimental task slightly differed from a real golf situation. In the golf situation, the ball has to fall in a hole. As a result, the subject must correctly judge the direction of the movement rather than overshoot the target. As frequently emphasized by expert players, "never up, never in". The consequence of this behavior is that the ball can fall in the same hole at different velocities. In the present experiment, such behavior would probably increase the intra- and inter-subject variability, presumably attenuating the effects of the experimental factors. For this reason, the subjects were encouraged not only to control precisely the direction of the movement, but also to control precisely the amplitude of the movement by trying to stop the ball on the target.

3. Results

For the purpose of analysis, only successful movements were considered and broken into two sub-movements: the Backswing (BS) and the downsing (DS) movements. The BS was initiated at the starting position of the club close to the ball and terminated at the highest position of the club when it moved back from the ball. The DS was initiated at the terminal position of the BS and terminated at the highest position of the club after contact with the ball. In the following sections, we will first present the results of the DS movement, and then those of the BS movement. This was justified by the fact that it is the DS movement which produced the force necessary to reach a given target.

The main dependent variables were the starting position of the movement, movement amplitude, movement time, and movement velocity. For each dependent variable, a Group × Distance (2 × 4) analysis of variance (ANOVA) with repeated measures on the last factor was applied. The means and the standard deviations are given in Table 1. When necessary, further analyses were also performed.

3.1. DS movement characteristics

3.1.1. DS amplitude

The DS amplitude was larger for the expert players than for the control subjects (671 mm vs. 520 mm, $F(1,9) = 3.7, p < 0.05$). It also increased with increasing the distance of the target (354, 541, 677 and 810 mm for the 1, 2, 3 and 4 m distances, respectively, $F(3,27) = 118.2, p < 0.001$). The interaction of Group × Distance also reached significance ($F(3,27) = 3.2, p < 0.05$). The effect of Distance was greater for the control subjects than for the expert players.

The DS movement was divided into two successive phases. The first phase was initiated at the end point of the BS movement and terminated at the contact with the ball. The second phase was initiated at the contact with the ball and terminated at the final position of the movement. This phase can be viewed as an accompanying movement of the ball after contact with the club. Frequently, the expert players empirically indicated that the contact of the club with the ball occured more or less at the end of the first-third of the DS movement. Doing that allowed the players to hit the ball when the club was still in the acceleration phase and resulted in a better contact with the ball. In order to investigate this question, we compared the amplitude of the first and the second phases of the DS. A Group × Phase × Distance (2 × 2 × 4) ANOVA with repeated measures on the last two factors was applied to the data.

Overall, the amplitude of the second phase of the DS was larger than the amplitude of the first phase (374 mm vs. 228 mm, $F(1,9) = 7.8, p < 0.05$). As suggested by the previous analysis, the amplitude of both phases increased with increasing the distance of the target (179, 274, 343 and 409 mm, for the 1, 2, 3, and 4 m distances, respectively, $F(3,27) = 116.3$, $p < 0.001$). The main effect of the Group was not significant ($p > 0.05$). The results also showed significant two-way interactions of Group × Phase ($F(1,9) = 6.6$, $p < 0.05$) and Phase × Distance ($F(3,27) = 9.2$, $p < 0.001$), and a three-way interaction of Group × Phase × Distance ($F(3,27) = 5.4$, $p < 0.01$). The interaction of Group × Phase showed that, for the control subjects, the amplitude of the two phases of the DS was not different (246 mm vs. 290 mm, $p > 0.05$). For the expert players, the amplitude of the second phase of the DS was twice that of the first phase (210 mm vs. 459 mm, $p < 0.001$). The interaction of Phase × Distance showed that the effect of Phase was greater when increasing distance of the target (ps < 0.01). The decomposition of the three-way interaction of Group × Phase × Distance showed, for the control subjects, a nonsignificant difference between both portions of the DS movement for the 1 and 2 m distances (ps > 0.05). For the 3 and 4 m distances, the amplitude of the second phase was larger than the amplitude of the first one (ps < 0.001). For expert golfers, the amplitude of the second phase of the DS was twice that of the first one, whatever be the distance of the target (ps < 0.001).

In summary, the increase in DS amplitude with increasing distance of the target was observed both for the first and second phases of the movement. The higher the force to be applied to the ball, the larger was the amplitude of the first and second phases of the DS. Furthermore, for the control subjects, the impact of the club with the ball occurred approximately in the middle of the DS movement, especially at 1 and 2 m. For the expert players, the contact of the club with the ball occurred roughly at the end of the first-third of the DS movement. The expert players better accompanied their movement once the ball was hit. Fig. 1 shows the typical behavior of an expert player and a control subject for the four distances. For the control subject, the path of the movements had a higher curvature than that for the expert player. It also differed as a function of the force required to produce the movements. Conversely, though the movements of a golf player showed

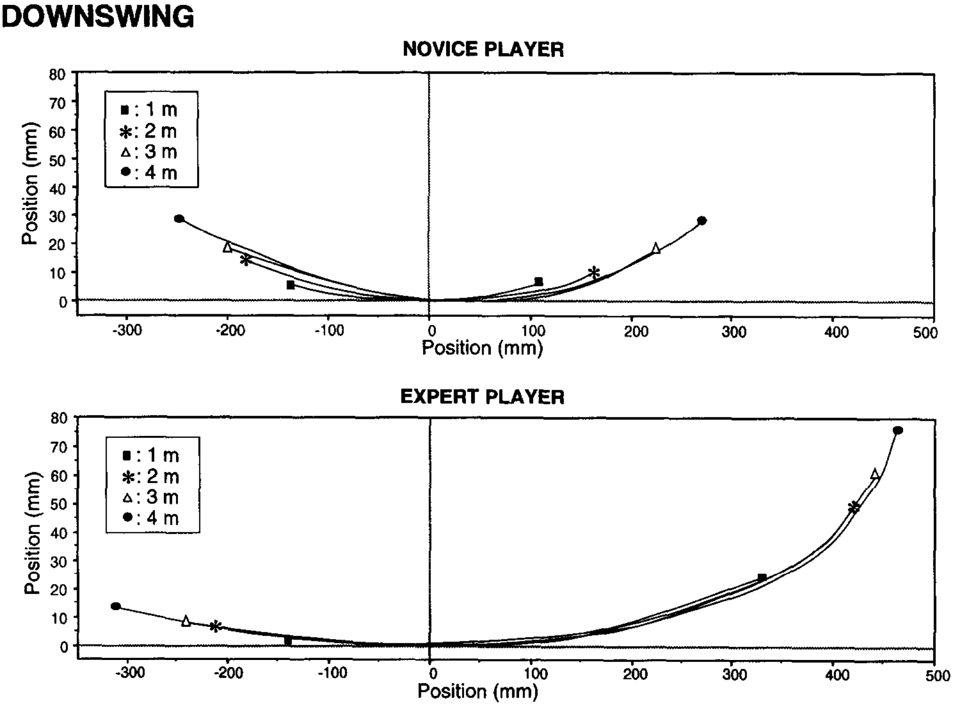

Fig. 1. Illustration, for the four distances, of typical bi-dimensional DS movements for a control subject (upper figure) and an expert player (lower figure). The vertical dashed line represents the moment of contact of the club with the ball. One should notice that the x and y scales are different; the real downswing movements are more planar and have a greater length than that suggested by the figure.

similar paths, the length of the path differed as a function of the force required to hit the ball (i.e., the distance of the target). However, the paths of the BS and the DS movements until the contact with the ball were perfectly superimposable.

3.1.2. DS movement time

The purpose of this series of analyses was to investigate the temporal control of the DS movement. A first Group × Distance (2 × 4) ANOVA was applied to movement time. Movement time was shorter for the control subjects than for the expert players (563 ms vs. 709 ms, $F(1,9) = 5.5, p < 0.05$). It increased with increasing distance of the target ($F(3,27) = 9.1$, $p < 0.001$). Post-hoc comparisons showed that movement time was shorter at 1 m than at the other three distances (*ps* < 0.001), and was not different (*ps* > 0.05) for the 2, 3 and 4 m distances (596, 649, 649, and 651 ms for the 1, 2, 3 and 4 m distances, respectively). For both groups, these data suggested an isochrony of the DS movement for the 2, 3 and 4 m distances. However, as suggested by Gentner (1987), an absence of a significant difference on movement time does not necessarily reflect the behavior of most of the subjects. Indeed, a nonsignificant difference can be obtained in two main cases. If movement time between two conditions is not different for most of the subjects, the isochrony of the movement can be confirmed. If, however, movement time increases for some of the subjects and decreases for the others, a nonsignificant difference on movement time is also observed, but the isochrony of the movement cannot be supported.

In order to investigate this question, a subject by subject analysis was performed using the test of Vinter and Mounoud (1991). According to these authors, the degree of isochrony can be estimated by the equation, $\log V = K + b \log p$, in which V represents the mean movement velocity, p the movement amplitude and K a constant. A perfect isochrony of the movement is demonstrated when b is equal to 1.

For each subject, the results showed slope values close to 1 (see Table 2) with a mean value of 0.9 for the experts and 0.8 for the control subjects, with high coefficients of correlation for both groups (0.98 and 0.94 for the expert players and the control subjects, respectively, *ps* < 0.001). These data suggested a strong tendency towards an isochrony of the movement. Fig. 2 shows typical linear regressions for a control subject and an expert player. One can notice the higher dispersion exhibited by the control subject when compared to the expert player. Furthermore, for the expert player, the different coordinates were concentrated in four areas corresponding to the four

Table 2
The coefficient of correlation, intercept and gradient ($p < 0.05$) of the linear regression between movement velocity and amplitude for each subject for the total DS movement and the DS to impact

		Downswing			Downswing to impact		
		R	Intercept	Gradient	R	Intercept	Gradient
Novice subjects	1	0.97	−2.32	0.84	0.95	−1.95	0.79
	2	0.96	−2.19	0.83	0.96	−2.08	0.88
	3	0.97	−2.97	1.09	0.98	−2.15	0.85
	4	0.98	−2.2	0.79	0.97	−2.34	0.96
	5	0.97	−2.29	0.84	0.96	−1.88	0.78
	6	0.94	−2.11	0.80	0.79	−1.59	0.67
	7	0.96	−1.83	0.67	0.95	−1.86	0.79
	8	0.89	−2.3	0.82	0.94	−1.89	0.79
	9	0.93	−2.14	0.77	0.87	−2.25	0.93
	10	0.84	−1.74	0.60	0.93	−1.63	0.64
Expert subjects	1	0.99	−3.58	1.30	0.99	−2.41	0.94
	2	0.96	−2.76	0.96	0.98	−2.49	0.92
	3	0.98	−2.1	0.75	0.98	−2.24	0.92
	4	0.98	−2.44	0.88	0.97	−2.01	0.82
	5	0.99	−2.05	0.74	0.98	−1.7	0.70
	6	0.99	−2.83	0.94	0.99	−2.37	0.93
	7	0.98	−2.01	0.71	0.99	−1.79	0.72
	8	0.99	−2.51	0.87	0.98	−2.21	0.89
	9	0.97	−3.01	1.03	0.95	−1.78	0.73
	10	0.98	−2.34	0.83	0.99	−2.11	0.86

distances of the target and confirming the greater stability of the experts' behavior.

Most of the studies on movements of interception have analyzed the DS movement only until the contact with the ball. For example, this was the case in table tennis (Tyldesley and Whiting, 1975; Bootsma and Van Wieringen, 1990), field hockey (Franks et al., 1985; Burgess-Limerick et al., 1991) and squash (Wollstein and Abernethy, 1988). In order to compare our data to previous studies, we investigated whether or not there was also an isochrony of the movement on the first part of the DS. A Group × Distance (2 × 4) ANOVA was applied to the duration of the first phase of the DS. Results showed that movement duration increased with increasing distance of the target ($F(3,27) = 8.5, p < 0.001$). Post-hoc comparisons showed that movement duration was shorter at 1 m than at the other three distances ($ps < 0.01$), and was not different ($ps > 0.05$) for the 2, 3 and 4 m distances (262, 274, 276 and 281 ms for the 1, 2, 3, and 4 m distances, respectively). There was no effect of

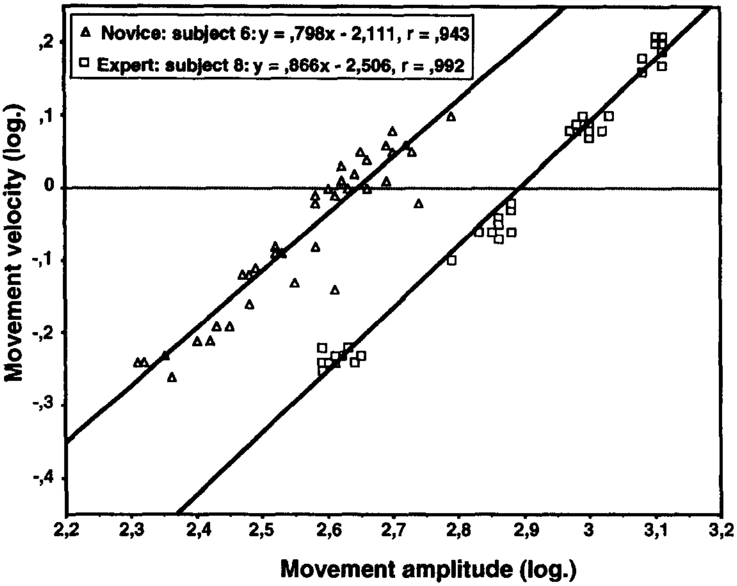

Fig. 2. Example of the linear regression of the relationship between movement velocity and movement amplitude (both expressed in logarithms), for a representative control subject and expert player.

Group ($p > 0.05$). The interaction of Group × Distance also reached significance ($F(3,27) = 2.6, p < 0.05$). For the control subjects, there was no significant effect of Distance ($ps > 0.05$). For the expert players, movement time was shorter at 1 m ($ps < 0.001$) than at the other three distances, and was not different for the 2, 3, and 4 m distances ($ps > 0.05$).

As for the previous analysis of the complete DS movement, a log-regression analysis between movement velocity and movement amplitude was computed for each subject. The slope values of the regression lines were close to 1 for both groups (0.84 and 0.81 for the experts and the control subjects, respectively) with high coefficients of correlation (0.98 and 0.93 for the expert players and the control subjects, respectively, $ps < 0.001$; see Table 2). Slope values were higher than 0.8 for seven subjects in each group (i.e., for 70% of the subjects). These data demonstrated a tendency towards an isochrony of the first portion of the DS movement, whatever be the subjects' level of expertise.

In order to investigate the temporal location of peak velocity, we compared the duration of the DS until peak velocity to the duration from peak velocity to DS end. A 2 Group × 2 Movement Phase × 4 Distance ANOVA with repeated measures on the last two factors was applied to the data. Results showed that the duration of both phases were longer for the expert players than for the control subjects (355 ms vs. 281 ms; $F(1.9) = 5.5$, $p < 0.05$). The main effect of Phase was not significant ($p > 0.05$). However, there was a significant effect of distance ($F(3,27) = 9.2$, $p < 0.01$). Analysis of the simple main effects showed an increase of the duration between 1 m and the other three distances, with no difference between 2, 3 and 4 m. For both groups, there was a trend towards an isochrony of the DS movement with peak velocity occurring approximately in the middle of the movement.

3.1.3. DS velocity

The purpose of this analysis was to control whether or not, for each distance, the two groups hit the ball with the same velocity. Indeed, the club velocity on contact with the ball is an essential requirement for the success of the task. The club velocity (i.e., the force applied to the ball) must be specified as a function of the distance of the target. Theoretically, for each distance, both groups should hit the ball with similar velocities. Results, however, showed that club velocity on contact with the ball was higher for the control subjects than for the expert players (1.5 m/s vs. 1.3 m/s, $F(1,9) = 9.5$, $p < 0.01$) and increased with increasing distance of the target (0.89, 1.28, 1.6 and 1.94 m/s for the 1, 2, 3 and 4 m distances, respectively, $F(3,27) = 2898$, $p < 0.001$). The interaction of Group × Distance also reached significance ($F(3,27) = 10.6$, $p < 0.001$). The effect of distance was greater for the control subjects than for the experts.

Interestingly, observation of the data (Table 1) showed that for the two groups and the four distances, the duration and amplitude of the first part of the DS until peak velocity were similar to the duration and amplitude of the second part of the DS from peak velocity to the end of the movement. A Group × movement Phase × Distance (2 × 2 × 4) ANOVA applied both to the duration and amplitude of each phase did not show a main effect of Phase and any interaction of this factor with the others (ps > 0.10).

3.2. BS movement characteristics

3.2.1. Starting position of the BS

Subjects were free to initiate their movement wherever they wished. The starting position of the club with respect to the ball was estimated by calculating the distance between the initial position of the ball and the club. The ANOVA showed that the expert players started their BS movement with the club closer to the ball than the control subjects (6 mm vs. 20 mm, $F(1,9) = 5.6, p < 0.05$).

3.2.2. BS amplitude

Analysis of the BS amplitude showed a significant main effect of Distance ($F(3,27) = 235, p < 0.001$), and no effect of Group ($p > 0.05$). The amplitude increased with increasing distance of the target (138, 200, 250 and 297 mm, for the 1, 2, 3 and 4 m distances, respectively). The typical behavior of an expert player and a control subject is illustrated in Fig. 3. The amplitude of the BS was not different for the two subjects. For the path of the club, observations similar to those reported for the DS movement could be made. The expert player initiated the movement closer to the ball, and finished it at a

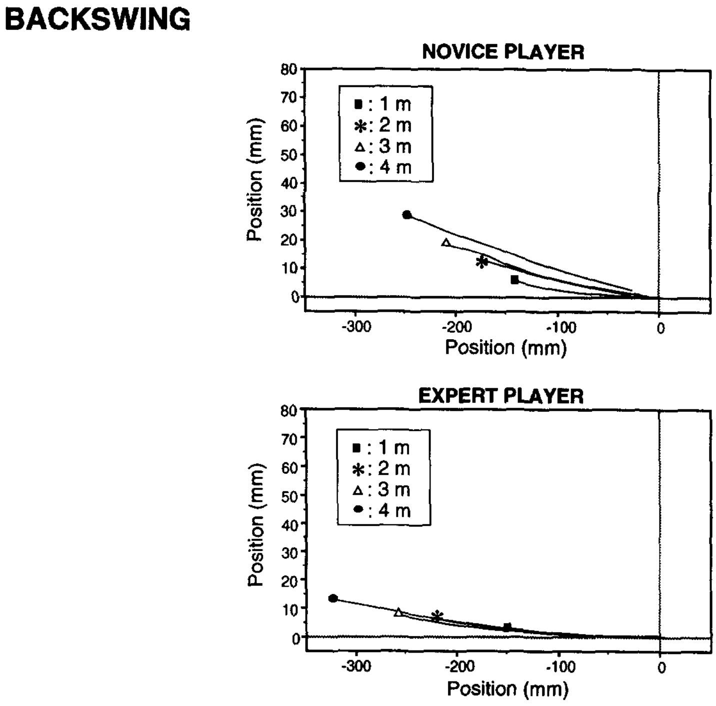

Fig. 3. Illustration, for the four distances, of typical bi-dimensional BS movements for a control subject (upper figure) and an expert player (lower figure). The vertical line represents the moment of contact of the club with the ball. One should notice that the x and y scales are different; the real BS movements are more planar and have a greater length than that suggested by the figure. For the control subject, the starting point of the backswing differed from one trial to another.

position lower than that of the control subject. As a result, the expert player exhibited a more planar path than the control subject, almost parallel to the plane of the green. Furthermore, for the control subject, one could observe that the path of the club varied with the distance of the target whereas for the expert players it was very similar for all distances.

3.2.3. BS movement time

As for the DS movement, the purpose of this series of analyses was to investigate the temporal control of the BS movement. Results of the ANOVA showed that BS movement time was longer for the expert players than for the control subjects (584 ms vs. 486 ms, $F(1,9) = 5.4, p < 0.05$). It also increased significantly with increasing distance of the target (457, 527, 563 and 591 ms for the 1, 2, 3 and 4 m distances, respectively, $F(3,27) = 117.2, p < 0.001$). Results of this analysis did not show the existence of an isochrony of the BS movement across the different distances.

4. Discussion

The purpose of the present experiment was to investigate better movement control for impact movements such as golf putting, when no spatial and temporal constraints were imposed on the subjects. More specifically, we investigated whether subjects increased the impulse of the force by (1) increasing the amplitude of the impulse and keeping movement time constant, (2) keeping the amplitude of the impulse constant and increasing its duration, or (3) changing both the amplitude and duration of the impulse. The way expert players and control subjects controlled the movement was also studied.

4.1. *Effect of distance putting on the spatio-temporal characteristics of the movement*

Beyond a simple description of the movement of putting for each group, common spatial and temporal characteristics can illustrate how force production is controlled in an impact movement for which the force increases with increasing distance of the putt. When analyzing the spatial characteristics of the movement, results for both groups showed that all dependent variables increased with increasing distance of the target. More interestingly, for both groups peak velocity occurred in the middle of DS amplitude.

Regarding the temporal characteristics of the movement, results showed that DS velocity was proportional to its amplitude so as to keep DS movement time until percussion and total DS movement time approximately constant with increasing distance of the target (Fig. 2). In other words, subjects increased the force applied to the ball by increasing the amplitude of the impulse rather than increasing its duration. This isochrony principle, originally studied in unidimensional movements, characterizes various motor skills such as manual pointing (Fitts, 1954), drawing or handwriting (Viviani and Terzuolo, 1980, 1982, 1983; Viviani and McCollum, 1983; Vinter and Mounoud, 1991), head rotations (Zangemeister et al., 1981), grasping (Jeannerod, 1984), or kicking of a ball by children (Thelen and Fisher, 1983). In golf putting, the tendency towards an isochrony of the movement and the fact that peak velocity occurred approximately in the middle of the DS amplitude seem to be intrinsic characteristics of the subject-club system. Furthermore, these characteristics are maintained constant even when modifying, through learning and experience, some components of the movement. For example, Vinter and Mounoud (1991) also showed an isochrony of the movement with children having limited experience in drawing. In golf putting, the isochrony principle would facilitate programming of the movement, whatever be the subjects' level of expertise.

Results also showed that, for all distances, peak velocity occurred approximately in the middle of the DS movement time. This is consistent with force control models in which the control system refers to a scaling of force amplitude maintaining a relatively constant force duration (Freund and Büdingen, 1978; Ghez, 1979; Schmidt et al., 1979; Meyer et al., 1982; Ulrich and Wing, 1991). More specifically, these models predict a similar shape of the force–time function when force amplitude varies while maintaining force duration constant. Interestingly, in the present experiment, no spatial and temporal constraints were imposed on the subjects, contrary to what was done in the experiments which have validated the models mentioned above. As already suggested above, this confirms that some characteristics of the movement of putting are intrinsic properties of the subject-club system.

4.2. *Effects of practice on force control*

In the previous section, we discussed the common spatial and temporal characteristics of the movement for both groups. The differences linked to the level of practice will be discussed now. Regarding the spatial characteristics of the movement, and more precisely the location of the impact on the

DS trajectory, results for the expert players showed that the amplitude of the second phase of the DS, i.e., after the contact with the ball, was twice the amplitude of the first phase, whatever the distance of the target. This behavior was in complete agreement with the instructions the players received during learning. Indeed, a strong emphasis was put on trajectory production. Producing a DS movement with the amplitude of the second phase being twice the amplitude of the first phase implied hitting the ball during the acceleration phase of the club (peak velocity being located after the contact with the ball), and allowed a more precise contact with the ball. When the movement was stopped just after the contact, the ball did not roll but only slided with a slight backwards rotation. As a result, the ball tended to bounce with a risk of deviation from its initial trajectory, and lost some of the energy necessary to reach the target. Accompanying the ball after the contact helped in reducing these perturbations. In other words, the goal of the movement was not limited to a simple contact with the ball. It consisted of a movement with the ball which was a movement as stable as possible from one trial to another, and from one condition to another. This stability of the movement was confirmed when analyzing the trajectories. As shown in Fig. 1, the expert players performed planar movements almost parallel to the plane of the green, and quite superimposable whatever the distance of the target. A more planar movement reproduced quite systematically from trial to trial would allow one to center the ball better with the "sweetspot" of the club, i.e., the best striking area of the putter, allowing in turn a reliable length of the putt.

Results for the control subjects indicated that the amplitude of the second phase of the DS, i.e., after contact with the ball, was smaller than that for the experts. More specifically, for the control subjects, the two phases of the DS had a similar amplitude. In other words, contact with the ball occurred approximately in the middle of the DS movement. The analysis of the movement trajectories also showed that they were much less planar for the control subjects than for the expert players (see Fig. 1). For the control subjects, producing movements having the same amplitude and shape before and after contact with the ball (i.e., which were symmetrical with respect to the ball) was the simplest way of standardizing their motor responses. Indeed, there was no a priori reason for executing movements with different amplitudes before and after contact with the ball; the more logical pattern was probably the one of a pendulum.

Regarding the temporal characteristics of the movement, results showed that BS movement time was shorter for the control subjects than that for the expert players. The BS movement was executed with a greater velocity by the control subjects than by the expert players, suggesting that the preparation phase of the DS was more tunely controlled by the expert players. Duration of the DS movement was also shorter for the control subjects than for the expert players. This was expected since DS amplitude was much smaller for the control subjects than for the experts, and movement velocity very similar for both groups. Surprisingly, the velocity of the putter on the contact with the ball was higher for the control subjects than for the expert players. In order to reach a target, the velocity of the club on contact with the ball should be similar for both groups for a given distance of the target. Two complementary explanations, at least, can account for this discrepancy. The first explanation assumes that the energy produced by club velocity was not entirely transferred to the ball. *During the contact*, there would be a greater loss of energy for the control subjects than for the expert players. The second explanation assumes a greater loss of energy *during the travel of the ball* for the control subjects than for the expert players, the ball bouncing much more during its travel on the green. In both cases, it is the orientation of the head of the club at the contact with the ball which would be responsible for these losses of energy. A curvilinear trajectory of the club probably induced a less efficient control of this orientation.

In summary, results of the present experiment suggested that control subjects and expert players used a similar behavior to perform the task. That is, to control movement velocity by increasing the amplitude of the impulse while keeping movement time and the temporal structure constant. This behavior would be directly dependent on the dynamic properties of the system and on the task constraints (Ulrich et al., 1995). It would also allow to reduce the complexity of the task by partly reproducing the movement of a pendulum. As shown by classical laws of physics, the movement of a pendulum without impact is perfectly isochronic whatever be the starting height. Furthermore, its peak velocity occurs in the middle of movement time and amplitude.

In a control experiment, we recorded the movement of the putter as similuted to a pendulum and submitted to gravity forces. It was released at four different heights such that, after contact, the ball reached the specified target. As given in Table 1, the amplitude of the movement increased on increasing the distance of the target, while movement time until impact remained constant. Furthermore, the amplitude and the time to impact were larger for the pendulum than for the subjects. Interestingly, peak velocity for the pendulum occurred at the moment of impact as for the control subjects. More specifically, mean velocity until impact and until peak velocity were similar for both the pendulum and the control subjects, suggesting that control subjects spontaneously reproduced the behavior of a pendulum. Interestingly too, mean velocity until peak velocity (but not until impact) was very similar for both the pendulum and the expert players. In other words, the expert players, through learning, had modified the moment of impact, reproducing, however, the mean velocity of a pendulum until peak velocity. This suggests that, whatever the subjects' level of expertise, the mean velocity until peak velocity is a constant depending on the properties of the subject-club system.

4.3. The determining role of BS amplitude in force control

The main characteristic of the movement which was modified with increasing distance of the target was movement amplitude, and thus club velocity on contact with the ball. In order to increase club velocity, i.e., the force applied to the ball with increasing distance of the target, the subjects would just need to specify the amplitude of the BS movement, maintaining the shape of the movement and the DS movement time constant. The larger the amplitude of the BS, the larger was de facto the amplitude in the first phase of the DS movement. It was also larger during the second phase of the DS, considering the instructions received during learning. As a result, the velocity of the club while travelling this larger DS amplitude within the same time was also higher. As already reported, control subjects exhibited a behavior similar to that of experts. However, control subjects achieved the movement with a similar amplitude and shape before and after contact with the ball. Furthermore, they exhibited a greater spatial and temporal variability than the experts (see Table 1) as frequently reported in numerous studies (e.g., Darling and Cooke, 1987; Young and Schmidt, 1990).

These results are reminiscent of the "operational timing" hypothesis proposed for an anticipation–coincidence task (Tyldesley and Whiting, 1975). These authors showed that in table tennis, the movement time until percussion of the ball was invariant across trials. It was proposed that the benefit of this strategy was to reduce the number of decisions (i.e., the number of degrees of freedom) taken into account before executing the movement to one, i.e., *when* initiating the drive. A similar behavior has been observed in various anticipation–coincidence tasks such as baseball (Hubbard and Seng, 1954), field hockey (Franks et al., 1985), squash (Wollstein and Abernethy, 1988), and table tennis (Bootsma and Van Wieringen, 1990). In impact movements, however, there is no temporal constraint. In this case, the purpose of keeping movement time constant need not be defined *when* initiating the drive, but rather the distance specified, so as to gather the necessary speed prior to contact with the projectile, i.e., to specify *where* (i.e., at which distance) the movement towards the ball is initiated. One should consider, however, that this behavior is probably valid for a given range of distances putted. A player cannot indefinitely increase movement amplitude for larger distances. It remains to be investigated how motor control is organized for larger distances of putting.

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