Jon Karlsen

Performance in golf putting

DISSERTATION FROM THE NORWEGIAN SCHOOL OF SPORT SCIENCES • 2010

ISBN nr 978-82-502-045-2

ACKNOWLEDGEMENTS

I have been competing in a lot of sports and games. I love competition, I love searching for the ultimate performance and I love golf!!

That's why I pursued a PhD related to performance in golf, and more specifically putting.

Johnny Nilsson has been my main supervisor. Words are not enough to tell what he has meant for my research career, but these two e-mails could help underline how much he has helped me:

Fra:	Johnny Nilsson [Johnny.Nilsson@gih.se]	Sendt: ti 19.12.2006 08:10
Til:	Jon Karlsen	
Kopi:		
Emne:	SV: "Stroke"-artikkel	
Vedlegg:		

Hallå Jon,

Tack för manus. Jag försöker köra igenom manus i natt och bör kunna ge dig återkoppling i morgon onsdag. Ha det bra.

Hilsen,

Johnny

Fra:	Johnny Nilsson [Johnny.Nilsson@gih.se]	Sendt: on 12.12.2007 10:39
Til:	Jon Karlsen	
Kopi:		
Emne:	SV: artikkel til World Congress	
Vedlegg:		

Jon,

Imponerande produktivitet! Jag jobbar gärna med din nya artikel och har tid i kväll/i natt. Ger dig feedback i morgon förmiddag. Intressant rubrik. Keep up the good work.

Hilsen,

Johnny

I would also like to thank Glyn Roberts (supervisor), Gerald Smith (supervisor), Ingar Holme (statistics), Camilla Karlsen (proof reading), Andreas Hagan, John Hellström, Vidar Jakobsen, Jan Cabri and other colleagues at the Norwegian School of Sport Sciences.

Horten, 29th January 2010

Jon Karlsen

ABSTRACT

Introduction

Putting, which accounts for about 40 - 45 % of shots in elite golf, is a complex skill. To perform in putting an elite player needs to master green reading, putter aim and technique. Mental skills, equipment and strategy may also affect performance. Although several research papers have been published on the subject of putting, only a few focus specifically on putting performance. The aim of the thesis is to investigate different factors affecting performance in golf putting for elite players, and to compare the importance of those factors.

Methods

A total of 190 players participated in five studies. Twenty-two of the subjects have played professional tournaments on the highest level in US or Europe, and 76 % of the players had a handicap of five or better. A 3D-kinematical putter analysis system (SAM PuttLab, Science&Motion GmbH, Germany) was used in a lab situation to investigate technique (Paper I), putter aim (Paper II), and how putter aim is affected by putter head design (Paper III). A new method to record putter aim was also developed (Paper II). Shaft weight influence on putting accuracy (Paper IV), and the determinants of distance variability (Paper V), have been investigated outdoors on regular putting greens.

Results

Direction variability (expressed as *SD*) caused by putter aim and technique for scratch players, was 0.92 and 0.54°, respectively. According to a variance analysis direction variability caused by green reading for a scratch player was estimated to about 1.3 - 1.6°. Club players rated mallet putters easier to aim with than blade putters, despite aiming blade putters more consistently (less variability). Putter shaft weight did not have any influence on putting accuracy, but club players hit the ball systematically shorter with heavier shafts. Preferred shaft weight according to subjective ratings was about 250 - 300 g combined with a 310 g putter head. A conservative estimate based on a variance analysis, showed green reading (60 %) to be much more important for distance variability than technique (34 %) and green surface inconsistencies (6 %).

Discussions/conclusions

In contrast to what is stated in the instructional literature and elite player practice, green reading seems to be much more important than technique both for precision in distance and direction. Equipment has little influence on putting performance, but putter fitting is anyhow recommended since any possible gain in performance can be achieved relatively easy. It is recommended that elite players should give high priority to green reading training, and coaches should focus on developing good methods to train green reading skills. Future research on the combination of green reading and mental preparation for the shot in the pre shot routine is suggested as the most important area for future research regarding elite performance in putting.

CONTENT

LIST OF PAPERS

The papers the present thesis is based on are presented below in order of appearence, and will be referred to by their Roman numerals:

I. Karlsen, J., Smith, G. & Nilsson, J. (2008). The stroke has only a minor influence on direction consistency in golf putting among elite players. *Journal of Sports Sciences*, 3, 243 - 250.

II. Karlsen, J. & Nilsson, J. (2008a). A new method to record aiming in golf putting - Applied to elite players", In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf V,* 395 - 401.

III. Karlsen, J. & Nilsson, J. (2008b). Golf players prefer mallet putters for aiming, but aim more consistently with blade putters, In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf V,* 402 - 407.

IV. Karlsen, J. & Nilsson, J. (2007). Club shaft weight in putting accuracy and perception of swing parameters in golf putting. *Perceptual and Motor Skills*, 2007, 105, 29 - 38.

V. Karlsen, J. & Nilsson, J. (2008c). Distance variability in golf putting among highly skilled players: The role of green reading. In, S. Jenkins (Ed.), *Annual Review of Golf Coaching 2008*, 71 - 80.

In addition some hitherto published and unpublished results are included.

INTRODUCTION

Accomplished golf performance depends on skills in driving, wood play, iron play, short game and putting, where putting often is considered the most important. Alexander and Kern (2005) found that putting ability was the most determining skill for earnings on the Professional Golf Association (PGA) Tour. In the 2009-season the world number one Tiger Woods hit 41.3 % of his shots from the green, a number which underlines the importance of putting (www.pgatour.com, 2009.11.20).

To perform well in putting a player needs both distance and line control. Green reading and technical skills are needed to perform in distance control, while green reading, aiming and technique are the abilities needed to perform good line control. A deterministic model of the major factors affecting performance in golf putting are depicted in Figure 1.

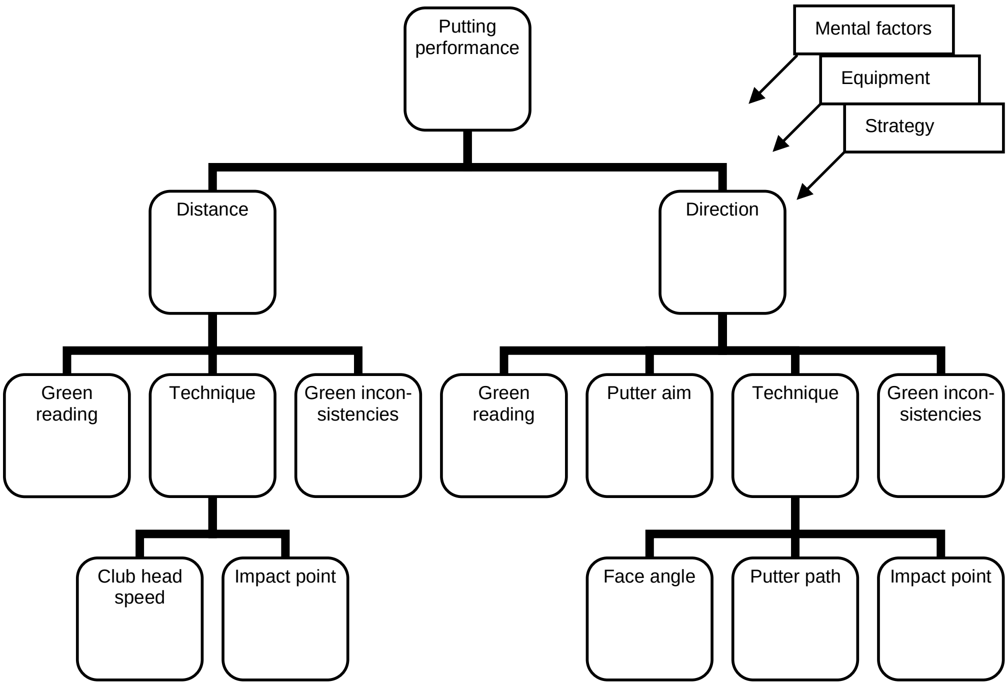

Figure 1. *Deterministic model of the major factors deciding performance in putting. Mental factors, strategy and equipment can affect putting performance at different levels in the model (adapted from Karlsen, Smith & Nilsson, 2008; Karlsen & Nilsson, 2008c)*

Golf and especially putting are mentally demanding. According to Nicholls (2007) putting is among the most frequently reported stressors among Scottish international amateurs. A study from McDaniel, Cummings and Shane (1989) who performed a questionaire on 1050 amateur and professional golfers, reported that 28.5 % of the players were affected by yips. Yips in golf are defined as involuntary movements during the performance of shots and the symptoms are spasm, jerks, tremors or freezing of the upper extremities. The scenarios where yips-affected strokes are reported most often are tournament and on short putts (e.g. McDaniel *et al*., 1989; Smith, *Malo & Laskowski.*, 2000).

Although performance in putting will depend mostly on the player, equipment, including the putter, may help to optimize the performance. Farraly *et al.* (2003) reported that 85 scientific papers across academic disciplines have been published on golf equipment between 1994 and 2003, but only a few of those have been related to putters. The perceived importance of the putter club may indirectly be shown by the large number of putter designs that exist on the market.

Players on different professional tours have a tight schedule with many tournaments and much traveling. According to the Official World Golf Ranking, male top 100 players play, on average, 25.7 official tournaments a year (www.owgr.com, 2009.10.22). Typically a tournament is four rounds over four days. Therefore it is essential for professional players to have knowledge of how different skills contribute to performance so they can make the right priorities in training. In addition it is important to have knowledge about how they can improve the different skills related to putting performance. The aim of the present work is to investigate and compare the importance of different factors affecting performance in golf putting.

Review of related literature

Over the last decades, a reasonable amount of putting research has been published. As indicated by the model in Figure 1, performance in putting is complex. A general weakness of the previous literature in putting is that it lacks a holistic view of performance. Typically, putting is investigated within only one academic field (e.g. biomechanics, motor learning, psychology, engineering) and results are often not considered in a putting performance context. In many studies putting has only been used as an arena to investigate general motor control problems, and putting performance itself has seemingly been only a second priority. In addition few studies have focused on elite players. Good exceptions are e.g. Marquardt (2007) who investigated the aim and technique of 99 professional players and Pelz (1994) who investigated green reading among players at all skill levels. Both these studies were conducted outdoor on real greens. What follows is a review of research on factors related to performance in putting.

Putting performance

Tierney and Coop (1998) manufactured a “world class model” putter based on data from PGA Senior Tour players. For performance on short putts, these data were compared with data from the ten best putters on the PGA Tour in 2009 (www.pgatour.com, 2009.10.24) and data from short putts test on various putts on a practice green by Norwegian elite players (mean handicap (hcp) = 0.0, 6000 putts) in 2009 (Karlsen, unpublished data, 2009) (Table 1).

Table 1. *The percentage of short putts holed by top 10 putters on the PGA Tour, the "World class model" putter by Tierney and Coop (1998) and by Norwegian elite players (mean hcp = 0.0) on putting tests (Karlsen, unpublished data, 2009)*

	PGA Tour top 10 putters	"World class model"	Norwegian elite players
1 meter	93.1 %	92.0 %	89.7 %
2 meter	64.2 %	65.0 %	56.9 %
3 meter	43.9 %	45.3 %	37.3 %
4 meter	30.7 %	31.5 %	25.1 %
5 meter	22.6 %	22.4 %	11.5 %

The "world class model", compares well with top PGA Tour putters for short putts. Tierney and Coop (1998) also estimated holing percentage for longer putts, percentage of 3-putts and expected number of putts for a world class putter (Figure 2).

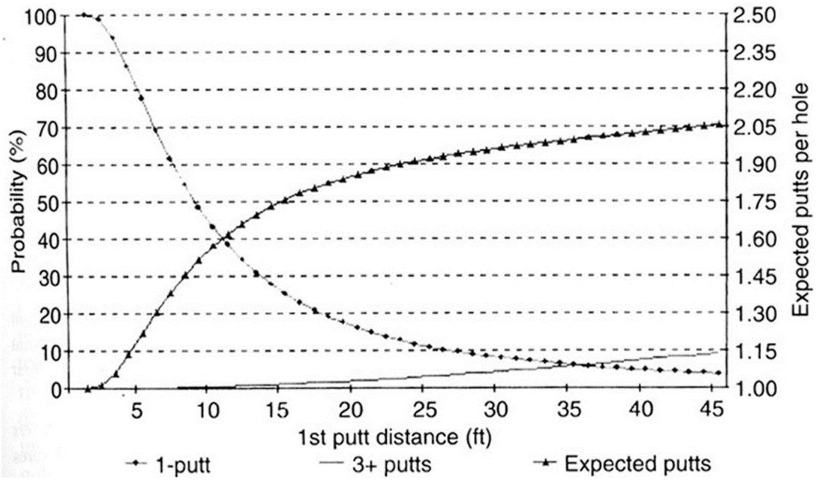

Figure 2. *"World class model", predicting 1-putt probability, 3-putt probability and expected numbers of putts taken from different distance by a world class putter (figure from Tierney & Coop, 1998).*

Some researchers have investigated putting performance broken down in direction and distance. Tierney and Coop (1998) estimated average distance and direction deviation for a world-class putter in tournaments to be 6.5 and 1.3 % of the putting distance, respectively. Karlsen (2003) found average relative distance and direction deviation for eight elite players (mean hcp = +1.5) to be 6.0 and 1.8 % during repetitive putts on a flat indoor green with a stimpmeter value of 11'[1].

Carnahan (2002) investigated the effects of slope and break on short putt (< 3.7 meters) performance in club players (hcp 6 - 30). They found putts that predominantly were uphill as the easiest to hole. However, they did not find any differences between left-to-right, right-to-left and downhill putts.

Technique

The purpose of the putting stroke is to start the ball with the intended speed on the intended line. Mechanically the initial ball start direction (stroke direction) is determined by three factors: the orientation of the putter face at ball contact (face angle), the direction of the putter head travel seen in the horizontal plane at ball contact (putter path), and contact point on the putter face at impact (impact point). The face angle affects the direction much more than the putter path. According to Pelz (2000) face angle will determine 83 % of initial direction, while putter path counts for the last 17 %. Nilsson and Karlsen (2006) found that horizontal miss-hits have little impact on initial ball direction. According to unpublished data from that study, deviation in initial ball direction caused by horizontal miss-hits on ten different putter designs was on average 0.34° per centimeter off center hit.

A debate going on for several years is, how the putter path and face angle should stay throughout the stroke. An important view from the coaching literature is presented by DeGunther (1996) and Pelz (2000). They advocate a putting stroke where the path is linear and the club face is square to the path (and the aim line) throughout the stroke. This view is adopted by many top coaches and players. An opposite view is supported by several researchers and coaches including Brooks (2002) and Swash (www.swashputtingschools.com, 2009.11.30). They advocate a stroke where the putter head moves inside the aim line in the backswing, and where the club face is square to the putter path, which means that the putter face is open to the aim line at the end of the backswing. Pelz´s argument for having the putter face square throughout the stroke is that timing limitations result in the inability to square the club face exactly at impact. The main argument against Pelz´s view is that the straight stroke is biomechanically complicated since it relies on a fully horizontal axis of rotation for the putter (Karlsen, 2003). Karlsen (2003) reported that upper body rotation around the spine is the major motor in putting for elite players, with a 70 % contribution to the club head speed. Keeping the spine in a position so the axis of rotation for the putter is horizontal requires a very forward bent address position, which is rarely seen. Therefore a straight stroke, for most players, must involve some kind of compensation which is considered to complicate the stroke.

[1] *A Stimpmeter^{TM} is a device that measures the speed of a green. Higher stimpmeter values means faster greens.*

Another stroke technique detail that has received attention is the spatio-temporal characteristics of the putter head throughout the stroke. Many coaches advocate a putting stroke where the putter has positive acceleration at impact (e.g. DeGunther, 1996; Pelz, 2000). Positive acceleration at impact is very often related to a stroke length ratio higher than one. Stroke length ratio is defined as the horizontal length of the follow through divided by the horizontal length of the downswing to impact. Stroke length ratio is more commonly used in golf teaching as it is easier to understand than acceleration. Delay, Nougier, Orliaguet & Coello (1997) compared elite and novice players and found that elite players had higher stroke length ratios (1.88 – 2.23) at 1 – 4 meter putts as compared to novices (1.14 – 1.28). Marquardt (2007) found a stroke length ratio of about 2.5 in professional players on 4 meter putts, while Karlsen (2003) found that eight elite players had a stroke length ratio of 2.35 at 2 meter, 2.17 at 8 meter and 1.78 at 25 meter putts. Pelz (2000) advocates a stroke length ratio of 1.2 independent of putting distance.

The tempo of the stroke, in terms of the duration of the downswing to impact, is also a parameter often used in putting instruction. Delay *et al.* (1997) found downswing time in expert players to be 261 – 289 ms on 1 – 4 meter putts. Karlsen (2003) found no differences in downswing time at 2, 8 and 25 meter putts for elite players. Average downswing times in that study were 305, 312 and 297 ms from 2, 8 and 25 metres, respectively, while Marquardt (2007) found downswing time among professional players to be 317 ± 35 ms. No research exists that evaluates downswing time in relation to direction performance. Marquardt (2007) also collected a huge amount of 3D-kinematic data of the putter movement from 99 professional players. All putts recorded were carried out at a distance of about 4 meters. The typical putting stroke of a professional player was a 1.1° outside-in putter path with a slightly opened putter face of 0.3°, hitting the ball 1.6 mm on the toe.

Hurrion (2009) compared PGA professionals with amateurs with regard to set-up and weight distribution throughout the stroke. The major differences between the two groups were that the professionals had their weight evenly distributed between left and right foot while the amateurs had about 60 % of their weight on the right foot. The amateurs also had a narrower stance and more lateral sway throughout the stroke. The head movement of golfers with different skill levels was also investigated. Lee, Ishikura, Kegel, Gonzales and Passmore (2008) found that expert golfers moved their head in the opposite direction of the putter, while less skilled golfers moved the head in the same direction as the putter. They did not conclude if any head movement strategy was more efficient than the other regarding performance.

Coello, Delay, Nougier and Orliaguet (2000) investigated putting technique from a movement control perspective in five expert players. They found that performance on short putts decreased significantly when vision of the putter head in the backswing was occluded (it was possible to see the putter at address). The variability of the duration of the downswing increased from 8 to 27 ms changing to the occluded vision condition. They concluded that the putting movement relied on real time visual control, and that golfers might be dependent on a short visuo-motor delay. A similar view is offered by Craig, Delay, Grealy and Lee (2000) who concluded that club head speed in putting in elite players is continuously regulated throughout the downswing.

Putter aim

Aim is the process of directing the striking face of the putter towards a target. This can be related to the ability of directing the body towards the target, which is normally termed “alignment”.

Different methods for measuring aim direction are used in research: fixating a putter to a rotatable mount (Neale & Andersson, 1966; Sidowski, Carter & O`Brian, 1973), laser beams which are reflected by the putter face (Neale & Andersson, 1966; McGlynn *et al.*, 1990), or inserted into the putter (Potts & Roach, 2002), 3D kinematical system (Karlsen, 2003; Marquardt, 2007). All researchers used accuracy (mean deviation from the target) as the performance measure, except Karlsen (2003) and Marquardt (2007) who reported precision (variability expressed as standard deviation).

MacKay (2008) compared eye-alignment with putter aim and found significant correlation between the two parameters ($p < 0.001$). He also found that 23 out of 30 players aimed right of the target, indicating systematic errors in the golfers tested who were between 40 and 60 years old, with handicaps between scratch and 20. Systematic errors in aim were also discovered by Mc Glynn, Jones and Kerwin (1990) who found that 64 % of the aims were to the left in a group of thirty players (hcp 2 - beginners). In contrast, Marquardt (2007) found that 99 Professional players on average aimed 0.35° right ± 1.56° and Karlsen (2003) found that eight elite players on average aimed 0.2° right ± 1.4°.

One limitation of earlier aim studies is that only 1 to 3 different targets were used. During a round of golf all putts are different and the ability to aim consistently at various targets with changes in light and shadows, grass cut lines, color contours etc. seem important for performance, and should therefore be reflected in a test. An advantage with a consistent (low variability) aim is that the player could use the same stroke on all putts. An overview of studies related to aim performance is shown in Table 2.

The effect of eye dominance on performance has also been investigated. Sugiyama, Nishizono, Takeshita and Yamada (2002) concluded that the right eye was most important in putting (right handed players), independent of eye dominance. They found that 48 students putted better from 3 m with the left eye closed than with the right eye closed. Steinberg, Frehlich and Tennant (1995) found that right eye dominant players performed better with the eyes positioned inside the ball and concluded that it was important to have a good view of the line with the dominant eye.

Table 2. *Summary of studies related to aim performance. A plus handicap (hcp) is a handicap better than scratch (zero).*

Source	Marquardt (2007)	Karlsen (2003)	Potts & Roach (2002)			Mc Glynn *et al.* (1990)			Sidowski *et al.* (1973)	Neale & Anderson (1966)	
n	99	8	9	9	9	10	10	10	60	10	10
Skill level	pro players	mean hcp = +1.4	mean hcp = 6.3	mean hcp =17.6	novices	hcp = 2 - 9	hcp = 11 - 20	beginners	beginners	mean hcp ≈ 25	mean hcp ≈ 25
Aim distance	4 m	2, 8 & 25 m	1.8 & 3.7 m	1.8 & 3.7 m	1.8 & 3.7 m	1.2, 2.4, 3.6, 4.8 & 6.0 m	1.2, 2.4, 3.6, 4.8 & 6.0 m	1.2, 2.4, 3.6, 4.8 & 6.0 m	0.6 & 1.8 m	1.5, 3.0 & 4.6 m	1.5, 3.0 & 4.6 m
Aim deviation (mean)			0.77°	0.78°	1.26°	2.11°	1.46°	2.05°	2.77°	2.82°	1.27°
Aim variability	0.67 ± 0.29°	0.57°									
Measuring method	3D system, while hitting balls, same target	3D system, while hitting balls, same direction	Laser putter, only aim, same direction	Laser putter, only aim, same direction	Laser putter, only aim, same direction	Laser, only aim, same direction	Laser, only aim, same direction	Laser, only aim, same direction	Rotatable mount & laser, only aim, 2 targets	Rotatable mount, only aim, traditional stance, 3 targets	Rotatable mount, only aim, croquet stance, 3 targets

Green inconsistencies

Although the standard of putting greens has improved over the years, even the best greens have unevennesses such as footprints, grass, mud etc. which will change the probability of holing a putt. With a True Roller^{TM}[1] (Pelzgolf, Spicewood, Texas), Pelz (1989) measured the inconsistency of greens, and found that 84 % of all putts from 12 feet (3.7 m) went in the hole on a green that was considered to be in excellent shape. At another well shaped golf course Pelz found that 73 % of the balls rolled into the hole in the morning before play, but after a day of play only 30 % were holed. In a similar study Koslow and Wenos (1998) found distance variability (expressed as *SD*) due to inconsistencies in the green to be about 0.9 % of the distance when they rolled balls from a secured ball ramp from 6 meter on an outdoor green. It is our experience that the quality of green surfaces has improved the last two decades. This means that the effect of green irregularities on consistency of ball roll could be somewhat smaller than the estimates done by Koslow & Wenos (1998) and especially Pelz (1989).

Equipment

The market trend over the last decade is an increasing number of mallet putter designs. The Odyssey 2-Ball putter, which in December 2002 peaked with a US market share of 28.5 % (www.golfweek.com, 2007.11.26, Schupak, A.), has led the way for larger popularity of creative putter designs. Many of these mallet putters have been marketed as putters which will make aiming/alignment easier. Two examples of marketing messages are: "These putters focus on revolutionary alignment and weighting technologies" - about the Odyssey 2-Ball models (www.odysseygolf.com, 2008.01.10) and "The Optigraphic Effect created by the body design and cavity insert improve your ability to align the putter with the target line" - about the Ping Jas Craz-E One (www.pinggolf.com, 2008.01.10). The work and research conducted by the putter manufacturers is hard to evaluate since they keep it confidential.

Some researchers have compared the performance of different putter designs. McGlynn *et al.* (1990) compared how easy different putters were to align at a target using players at all levels. They found a "rectangular-shaped aim-putter" to be significantly easier to align than four other designs. Gwyn, Ormond and Patch (1996) compared performance using different putter heads. They found no significant difference in putting accuracy between a traditional blade-putter and a cylindrically formed putter head.

The influence of putter length on performance is also studied. Pelz (1990) compared performance with long and conventional putters and concluded that the long putter was best on short putts (0.9 m), equally good on medium putts (2.7 m)

[1] *True Roller^{TM} is a ramp like device which can be used to roll out balls with consistent direction and speed.*

and the worst on long putts (6.1 m). Gwyn and Patch (1993) compared performance using long putters and putters with traditional length. They did not find any significant difference in number of putts taken by 88 novice players, when playing nine holes on a practice green.

Practical field discussions are often focused on the effect of club face grooves on ball roll in putting. Yes!™, which is one of the major putter manufacturers, claims that the C-Grooves™ on every Yes!™ putter solves the problem with skidding, side- and even back-spinning better than any other putter on the market (www.yesgolf.com, 28.11.2009). Brouliette and Valade (2008) compared grooved and milled putter faces with different loft for skid distance, but skid distance did not seem to be reduced by grooves.

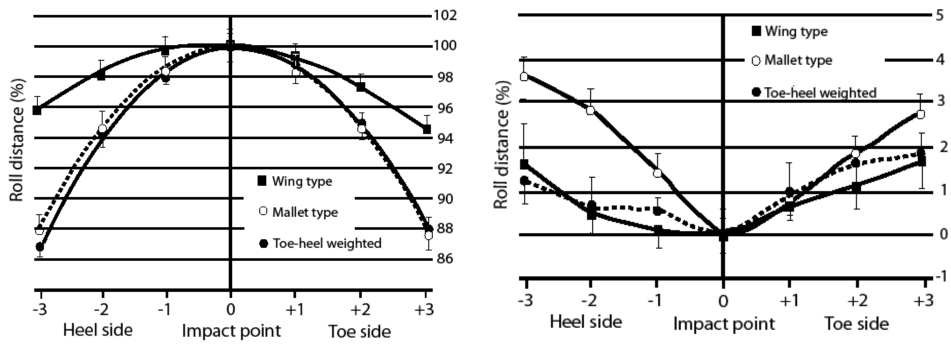

Figure 3. *(Left) The relationship between horizontal impact point and roll distance for three different putters. On the ordinate 100 % represents roll distance at impact point 0. (Right) The relationship between horizontal impact point and medio-lateral ball deviation in percent of roll distance for three different putters. In both plots the impact point 0 represents the sweet spot of the club head and 1, 2 and 3 represent deviation (in cm) of impact points to the toe (+) and heel side (-) of the putter face. Each data point in the figure represents the mean ± SD of 10 repeated ball impacts (figure from Nilsson & Karlsen, 2006)*

Putter head design can also affect how well a putter performs when contact is not at the "sweet spot. Nilsson and Karlsen (2006) designed a putter rig to measure the effect of miss hits. They found that a specially designed wing shaped putter performed better than a blade and a mallet putter both in distance and direction on horizontal miss hits (Figure 3). On a 2 cm horizontal off-center hit roll distance compared to a centre hit was reduced by approximately 5.5 % with the mallet and the blade putter while it was reduced approximately 2 % with the wing type putter. In a similar type of study Werner and Greig (2000) found that a measurable difference between two putters existed; which they called "the best" and "the poorest" of conventional putter design regarding performance on horizontal off-center hits. However, they concluded that the difference only would have a negligible influence on both directional and distance performance. They found that horizontal off center hits only explained 0.3 %, while club head speed explained

99.7 % of distance errors[2]. The effect of vertical off-center hits on distance errors was not investigated.

The weight of the putter is a factor that may have potential to affect performance. Although not common, club heads with large variation in weight are available (approximately 250 – 700 g, with most putter heads around 350 g). Traditional putter shafts weigh approximately 100 g for normal length (34” / 860 mm), but putters with shaft weight up to 500 g are used by some professional players, also. Nilsen (2008) investigated how shaft weight affected putter head kinematics and performance in 20 highly skilled players (mean hcp = 1.9) who tested six different putters with shaft weight ranging from 144 - 611 g (head weight = 292 g). A regression analysis showed that the players subjectively rated 290 g as the ideal shaft weight. The only difference in the kinematics was the increased time of the down swing to impact with increased shaft weight (144 g shaft = 349 ms, 611 g shaft = 367 ms). Furthermore impact occurred more towards the heel with lighter shafts (144 g shaft = 1.2 mm heel, 611 g shaft 0.6 mm toe). Nilsen also found that these golfers on average hit the ball shorter with heavier shafts, even though the target distance was 4 meters on all putts (144 g shaft = 4.10 m, 611 g shaft = 4.00 m; first putt in each series: 144 g shaft = 4.33 m, 611 g shaft = 3.89 m). A linear regression model showed better distance accuracy with heavier putters ($p < 0.05$). Mean relative distance error was 5.4 % with 144 g shaft and 3.8 % with 611 g shaft. However, there were no differences between putters with respect to precision.

Green reading and mental aspects of putting

Pelz (1994) did a study on green reading which has a large impact on putting teaching. He found that players at all skill levels, even tour professionals, only read about 25 % of the break, and then unconsciously compensated for poor break reading with their aim and technique. It seems, from personal experience, that the awareness of this phenomenon has increased among players and coaches over the last decade. Pelz also noted that almost all players read the break from behind the ball-hole line, and that plumb-bobbing did not affect the read. The latter is also supported by MacKenzie and Sprigings (2005) who concluded that “the plumb-bob method was found to be an invalid system for determining the break of a putt”.

Although difficult to quantify mental aspects of performing in putting seem very important. One indication of the importance of mental factors is the yips, which is uncontrolled movements in the forearms in putting. Various researchers reported the incidence of yips to be about 15 - 48 % (Marquardt, 2009). Yips can be detrimental to performance and typically occur on short putts. This corresponds to Nicholls (2007) who found that Scottish international amateurs reported putting as one of the highest sources of stress in tournaments. In two other studies by Nicholls and colleagues (2005*a* & *b*) “sticking to a pre-shot routine” was reported as an important stress coping strategy by Irish and Scottish international amateurs. This

[2] *Werner and Griegs’ results were recalculated with the method for estimating relative importance explained in Appendix 1.*

was also underlined by Tiger Woods (2005): “I can’t overstate the importance of a pre-shot routine. It helps with focus, rhythm and relieving tension in pressure situations”.

The pre-shot routine in putting is closely studied. Thomas, Neumann and Hooper (2008) found that elite players were more likely to focus their attention externally than players with lower skills. Beauchamp (1998) interviewed five PGA-Tour players regarding their psychological skills related to putting. Task focus, positive imagery and confidence were key aspects reported as being related to peak putting performance. The importance of task focus corresponds well with Thomas *et al.* (2008). Douglas and Fox (2002) investigated behavioral aspects of the pre-shot routine among 16 Ladies European Tour professionals. They found highly structured routines and consistent routine behavior. On average the elite players had 0.7 practice strokes, took 5.7 seconds from grounding the putter behind the ball to impact and had 1.9 glances at the hole after addressing the ball.

Strategy

If you target to drop the ball in the hole, the probability of ending up short is 0.5. Pelz (1989) introduced a rule that all putts should end up 0.43 meters past the hole if missed. This rule was challenged by Hoadley (1994). He suggested that the ideal aim was 0.61 meters multiplied with the probability of holing the putt, past the hole. This means that long putts should more or less drop in the hole while on shorter putts it is more effective to approach the hole with somewhat higher ball speed. According to Hoadleys model, Pelz`s strategy will give 0.06 more putts from 18.3 meters.

Aim of the thesis

The aim of the thesis is to investigate different factors affecting performance in golf putting for elite players, and to compare the importance of those factors.

The main research questions addressed in the present thesis are:

- How consistent are elite players in initial ball start direction?
- What are the characteristics of consistent putting technique?
- Is it possible to develop an improved method to record aim in putting?
- How consistent are elite players in putter aim?
- How important are green reading, putter aim, technique and green inconsistencies for direction consistency?
- How does putter head design affect aim performance?
- How will putter shaft weight affect performance?
- How important are green reading, technique and green inconsistencies for distance variability?

METHODS

In the present project a variety of methods were utilized. Furthermore, some new methods and equipment were also specifically developed for the project.

Participants

The intention in the whole project was to study high level competitive players. There was a trade off between accessability and the level of the participants since elite players often are less available for research projects than club players. Therefore, club players were used as participants in the projects regarding equipment. In the studies regarding aim, technique, distance control and green reading only highly skilled players were used. Players I have termed “highly skilled” or “elite” are players with a minimum of a single digit handicap up to world class professionals. Twenty-two of a total of 190 participants have played professional tournaments on one of the four largest professional tours (PGA, LPGA, ET & LET), and 76 % of the participants had a handicap of five or less. The characteristics of the participants are described in Table 3.

Apparatus

Both commercially available and equipment developed in-house were used in the different studies. In Paper I, II and III a 3D-kinematic system for recording golf putter movement was used (SAM Putt Lab, Science&Motion GmbH, Germany). In Paper II and III the 3D-kinematic system was used in conjunction with a specially developed aiming green. In the study of equipment (putters) both commercially available, and specially made putters were used (Paper III & IV). The different measurement systems and putters are described below.

3D-kinematic analysis system

For 3D-kinematic analysis of the putter movement and aim direction (Paper I, II and III) we have used SAM PuttLab which is a ultrasound system specially designed to record kinematics of the golf putter during the putting stroke. Attached to the putter was a triplet with three 70 Hz ultra sound transmitters, which sent out signals to a receiver unit (Figure 4) The SAM PuttLab comes with software (SAM PuttWare Pro version 1.1.), which automatically calculates about 50 parameters from the putting stroke. Because the players were expected to have small variability in putting technique, the system was tested for reliability in face angle which clearly is the most important putting direction parameter. One putter was mounted in the putter pendulum rig described by Nilsson and Karlsen (2006). The test included dropping the putter in the pendulum rig 2 x 20 times, and variability (calculated as *SD* in face

Table 3. *Characteristics of the participants in the different studies.*

Paper	*n*	Mean handicap	Mean age	Gender distribution (*n*)
I. ”The stroke has only a minor influence on direction consistency in golf putting among elite players”	71 (incl. 26 pros)	1.8 ± 4.2 strokes	21.7 ± 7.1 years	63 ♂ / 8 ♀
II. "A new method to record aiming in golf putting - Applied to elite players"	20 (incl. 13 pros)	+0.4 ± 2.6 strokes	25.6 ± 8.1 years	19 ♂ / 1 ♀
III. "Golf players prefer mallet putters for aiming, but aim more consistently with blade putters”	32 (incl. 4 pros)	11.4 ± 10.8 strokes	34.4 ± 14.7 years	30 ♂ / 2 ♀
IV. ”Club shaft weight in putting accuracy and perception of swing parameters in golf putting”	24 (incl. 2 pros)	12.4 ± 8.5 strokes	36.5 ± 14.9 years	21 ♂ / 3 ♀
V. "Distance variability in golf putting among highly skilled players: The role of green reading”	43 (incl. 8 pros)	2.8 2.2 strokes	20.2 ± 6.7 years	34 ♂ / 9 ♀

angle at an impact position) was recorded to be 0.09° and 0.10° for the two series. This variability was much smaller than the face angle variability measured in the putting strokes of the players in Paper I, which on average was 0.60°. Therefore, the SAM-system was assumed to be sufficiently accurate to measure the stroke direction variability of elite players.

Aiming green

To be able to measure aim performance in Paper III and IV we developed a new method since the methods described in the literature were considered insufficient. We made an artificial aiming green of about 6 x 4 meter with rounded edges (Figure 4). The green which was placed on a flat horizontal indoor surface, had one spot where the ball was positioned, and 16 different targets spread out in a 120° angle. There were eight close target points marked as black crosses in a distance of 0.4 - 1.3 meters away from the ball position, and eight distant target points with white paint as a filled circle at the size of a standard golf hole (diameter = 108 mm) placed 2.7 - 4.6 meters away from the ball position. The targets were numbered from 1 - 16, alternating between close and distant targets, and randomly distributed throughout the 120° range. The face angle was measured with SAM PuttWare.

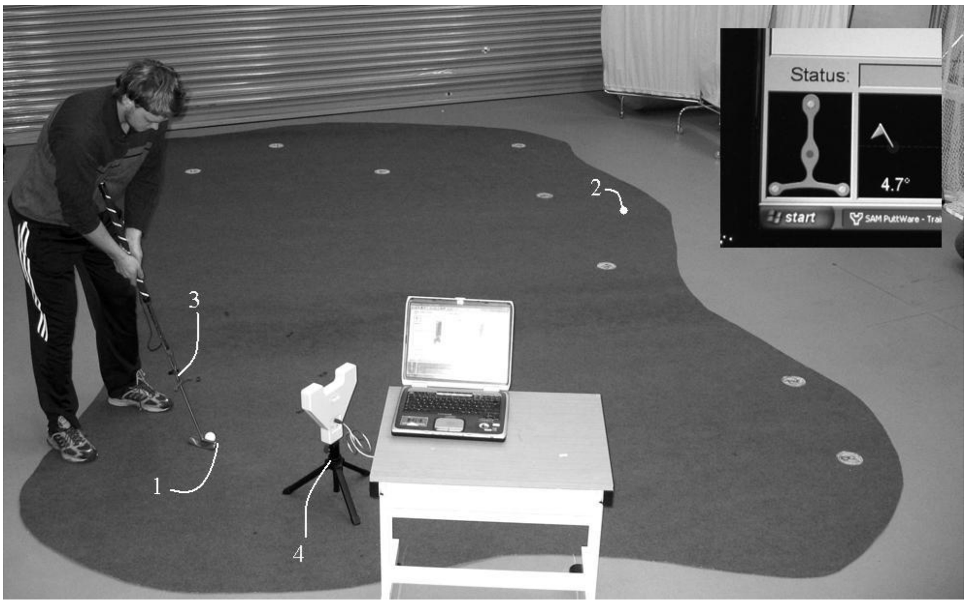

Figure 4. *Aiming green. (1) ball position, (2) calibration spot, (3) triplet with three ultrasound transmitters, (4) receiver unit. The inset picture shows the SAM System where face angle was read in real time with a resolution of 1/10th of a degree (Figure from Karlsen & Nilsson, 2008b)*

The angular position for each of the targets was carefully measured out both geometrically with an angle and a meter ruler, and with help of the 3D-system. No targets were on the same line from the start spot, which was a small bump in the green assuring the ball could be placed in position with high consistency. A calibration spot was marked approximately in the center of the 120°-range (Figure 4).

Putters

Different putters were tested (Paper III and IV).[1] In Paper IV three putters with different shaft weight (100, 420 and 610 g) were used. All shafts were made of steel. The normal putter had a traditional steel shaft (100 g) with a slightly increasing diameter from tip to butt. The two heavier putters had parallel shafts. The grip was of the same type and weight (60 g) on all putters. Putter head used in all putters was a toe-heel weighted model (Golfsmith Brassmaster, Austin, Texas) with a long hosel (74 mm), weighing 310 g.

In Paper III mallets and blades, which are the two main types of putter heads, were compared for aiming performance. The twelve putters included in the study are displayed in Figure 5.

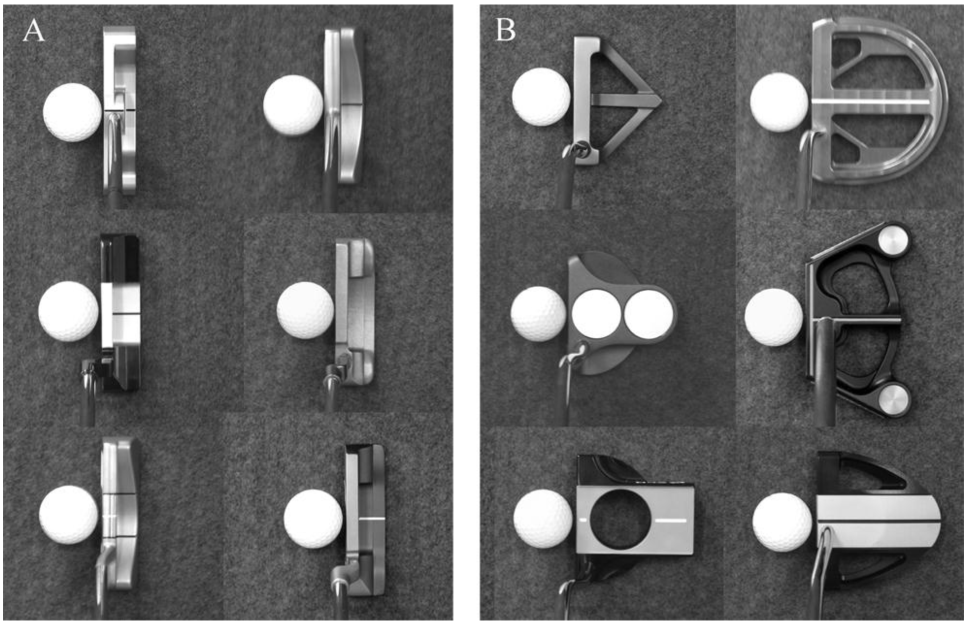

Figure 5. *(A) The six blade type putters used in the present study, (B) The six mallet type putters (Figure from Karlsen & Nilsson, 2008b)*

[1] It should be noted that the authors of Paper III and IV have interest in a company manufacturing one of the mallet putters with heavy shafts. Significance test and conclusions in Paper III are not affected if that particular putter is taken out of the study.

Study design/test procedure

Paper I - 3D-kinematic testing of putting technique

The data were recorded both indoor and outdoor, on flat and relatively fast greens. The players were instructed to strike the ball as consistently as possible on distance and direction to a target which was either a hole on the green or a painted hole on a putting mat. They hit the balls in their own chosen inter-stroke tempo with their own putter. Mean number of trials was 18.3 ± 5.1, and distance range was 3 – 4 m.

Based on how we perceived its relevance to putting teaching, four parameters were selected for analysis on how they were related to stroke direction consistency. “Face rotation” in the downswing was defined as the difference between the club face angle at the end of the backswing and at impact. “Face change” was the difference between the face angle at address and at impact. “Downswing” time was the time taken from the end of the backswing to impact and “stroke length ratio” was the horizontal length of the follow through divided by the horizontal length of the downswing to impact.

Paper II - Aim performance testing of elite players

The data were collected in the Biomechanics Laboratory at the Norwegian School of Sport Sciences. The aim performance test consisted of 1 - 3 series of 16 aims (mean aims: 27 ± 9) on the aiming green (Figure 4) with the players own putter. The player aimed with his/her normal strategy for aiming (e.g. “line on ball”), in preferred tempo. When the player was satisfied with his aim a signal was given to the test leader which read the face angle from the computer. No balls were hit, and no feedback was given during the test.

Paper III - Aim performance testing of golf putters

On the aiming green, each player did 16 aims with each of the twelve putters, one aim to each target, without hitting the ball. The order of putters was randomized, but the order of targets within each putter was always from 1 - 16. The players were not allowed to use a line on the ball to assist aiming. When the player was satisfied with his aim a signal was given to the test leader who read the face angle in real time from the SAM PuttWare 1.1 software. No balls were hit, and no feedback was given before all 192 aims were finished. After one putter was finished the subjects answered the question: “How easy, or difficult, do you think it was aiming with this putter?” by giving a rating according to the scale in Table 4. They rated the putter both for short and long targets, and they were allowed to use all integers from 0 - 100. It is also important to note that, for regular play, 18 of the 32 players (56 %) used a mallet putter.

Table 4. *Scale for subjective rating of how easy the putters were to aim at the target (Table from Karlsen & Nilsson, 2008b)*

100	-	Extremely easy
90	-	Very easy
80	-	
70	-	Easy
60	-	
50	-	Neither easy nor difficult (average)
40	-	
30	-	Difficult
20	-	
10	-	Very difficult
0	-	Extremely difficult

Paper IV - Comparing putters with different shaft weight

The data collection was carried out over three days on a flat part of an outdoor practice green (Figure 6). The green was cut every day before testing, and stimpmeter values were between 7' 6" and 8' 4". After "warm-up" of 30 putts, ten putts per club, each subject completed an additional number of 90 putts in the test. They performed 10 putts on each of the three distances: 4, 8 and 12 m. The three different putters tested were used in a random order. The order of distances (e.g. 4 - 12 - 8 m) within each club was also randomized, but each subject kept the same

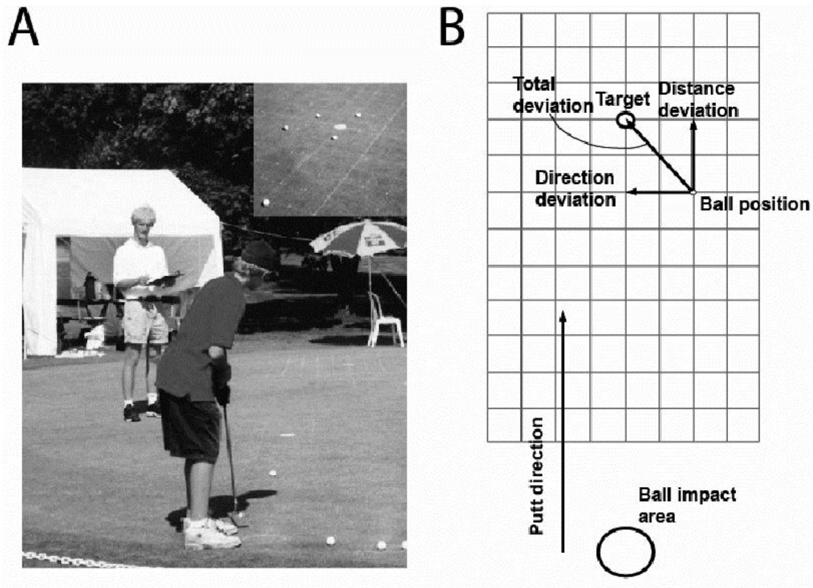

Figure 6. *(A) Picture from the test area. The inset picture shows one of the targets with the surrounding grid. (B) Schematic drawing of the test set-up on the putting green, including different deviation parameters (Figure adapted from Karlsen & Nilsson, 2007)*

order of distances in all three clubs. Before each new putt distance they had two "warm-up" putts. The subjects completed all 30 putts with one club, before changing to another club.

The target was marked on the green as a circular surface, the size of a golf hole (diameter: 0.108 m). Around the target a grid consisting of 0.2 x 0.2 m squares was painted on the green with thin chalk lines. The grid was used to simplify the measurements of deviation in putt distance and direction. To minimize tracks from the balls on the green, the participants hit the ball anywhere from a circular shaped impact area of about 0.3 m in diameter. The players were instructed to stop the ball exactly at the target.

After each series of ten putts all subjects rated the putter on "weight feeling", "feeling of stability in the downswing" and "overall feeling" on scales from 0 to 100 (Table 5).

Table 5. *Scales for rating of "weight feeling", "feeling of stability in the downswing" and "overall feeling" (Table from Karlsen & Nilsson, 2007)*

"Weight feeling"	"Feeling of stability in the downswing"	"Overall feeling"
100 - maximum heavy	100 - maximum stability	100 - extremely good feeling
90 - too heavy	90 - very stable	90 - very good feeling
80 -	80 -	80 -
70 - heavy (slightly too heavy)	70 - stable	70 - good feeling
60 -	60 -	60 -
50 - neither light nor heavy (perfect)	50 - neither stable nor instable	50 - neither good nor bad feeling
40 -	40 -	40 -
30 - light (slightly too light)	30 - instable	30 - bad feeling
20 -	20 -	20 -
10 - too light	10 - very instable	10 - very bad feeling
0 - very light	0 - no stability at all	0 - extremely bad feeling

Paper V - Distance control: the role of green reading

Testing was conducted during two days on an approximately 600 m^2 outdoor two-tiered practice green (Figure 7). On the two different tiers the green had some undulations, but some parts were also relatively flat. Stimpmeter values were recorded nine times in total over two days, and were on average 9'8" (range: 9'1" to 10'4"), which corresponds with the average reported stimpmeter values of 10'3" from PGA European Tour tournaments in 2006 (www.europeantour.com).

After a five minute free warm-up session, each participant performed a total of 70 putts on two different tests. Firstly, they played a 40-hole course ("40 putt test") with putts ranging from 2.2 to 19.3 meters (median distance = 6.0 m). The players were instructed to stop the ball as close as possible to a line on the green. Because of space limitations, the 40 different putts were arranged in seven different fields of 5 – 6 putts which had the same target line. The course was set up so the players always switched to a different field between each putt. After doing the "40 putt test" all players did 30 repetitive putts from the same starting spot to a target line 6 meters away (“30 putt test”). Also in this test they were instructed to stop the ball as close as possible to a target line. Green slopes were measured with a digital water level (Breakmaster, www.exelys.com). The average slope at the target lines in the seven different fields of the “40 putt test” were 0.2° ± 1.2° uphill, which corresponded to the average slope of the three different fields used for the “30 putt test” test of 0.1° ± 0.2° uphill.

Figure 7. *Picture of approximately two thirds of the green used in the distance control study. The numbers (1, 4, 5, 6 and 7) indicate the target lines for five of the seven fields in the “40 putt test”. The letters (a - f) indicate the start point for the six putts in field no. 1 (a = putt no. 1, 3.30 m; b = putt no. 8, 14.10 m; c = putt no. 15, 9.60 m; d = putt no. 22, 12.30 m; e = putt no. 29, 16.40 m and f = putt no. 36, 2.60 m). The arrow shows the general direction of the putts in field no. 1. The inset picture show the marking of the start spot for each putt (Figure from Karlsen & Nilsson, 2008c)*

Statistical methods

Regression analysis and conventional descriptive methods were utilized to describe the data that were collected. In addition Cohen`s *d* (Cohen, 1988) was used to calculate effect size (Paper III). Methods for repeated measurements with data initially tested for sphericity with Maucley’s test (Greenhouse-Geisser correction if significant), and Bonferroni corrected critical p-values were also applied (Paper IV). In Paper I and V stroke direction variability; the importance of face angle, putter path and impact point for stroke direction consistency; the importance of green reading, technique and green inconsistencies for distance variability were estimated by variance analysis. Calculation methods for variance analysis are explained in detail with examples in Appendix I and II. Calculations have been performed with the statistical softwares SPSS 15.0 (SPSS, Chicago, Illinois) and Excel 2003 (Microsoft, Redmond, Washington).

RESULTS

Technique

Stroke direction consistency

Stroke direction variability was on average 0.59 ± 0.22° (Paper I). The lowest variability, 0.28˚, was exhibited by a PGA European Tour player. According to the regression model in the present study an average European Tour player (handicap ~ +5.5) had a stroke direction variability of 0.39°. A regression analysis showed that stroke direction variability was related to playing handicap ($p < 0.001$) (Figure 8).

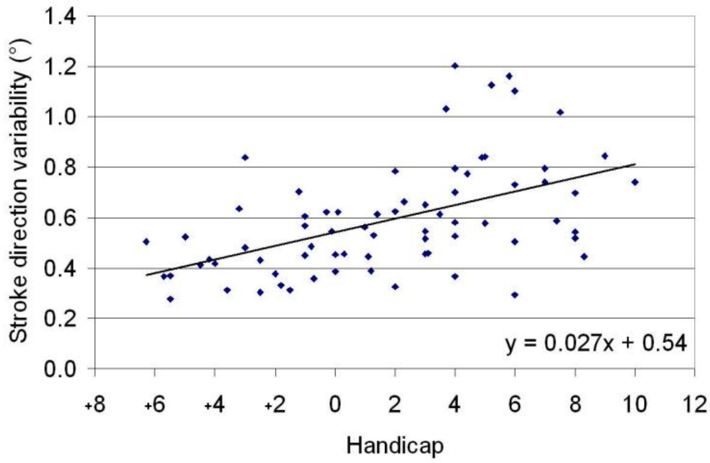

Figure 8. *Stroke direction variability (as standard deviation in degrees) for all 71 players relative to their handicap. Regression equation and line are included ($R^2 = 0.26$) (figure from Karlsen, Smith & Nilsson, 2008).*

Face angle, putter path and impact point

Elite players were more consistent in face angle than in putter path ($p < 0.001$) with average variability of 0.60 ± 0.22° and 1.04 ± 0.38°, respectively. Horizontal impact point variability was 2.72 ± 0.78 mm. Because face angle errors affect direction much more than putter path errors do, effective variability of face angle was much higher than for putter path. The effective variability of face angle, putter path and horizontal impact point was 0.50°, 0.18° and 0.09°, respectively (Effective variability = face angle variability · 0.83, putter path variability · 0.17 and horizontal impact point variability · 0.034 degrees·cm^{-1}). The relative importance of the three parameters regarding stroke direction consistency was 80 % for face angle, 17 % for putter path and 3 % for horizontal impact point (Table 6) (for calculation methods see Appendix 1).

Table 6. *Variability, effective variability and relative importance of face angle, putter path and horizontal impact point for stroke direction consistency. Variability results are mean values for 71 players ± standard deviation in degrees or millimetres. Total effective variability was 0.59° (Table from Karlsen, Smith & Nilsson, 2008)*

	Face angle	Putter path	Impact point
Variability	0.60 ± 0.22°	1.04 ± 0.38°	2.72 ± 0.78 mm
Effective variability	0.50 ± 0.18°	0.18 ± 0.06°	0.09 ± 0.03°
Relative importance for stroke direction consistency	80 %	17 %	3 %

Stroke characteristics

Four parameters were tested with a quadratic regression model to find optimum values for stroke direction consistency. The regression models were significant for three parameters: face rotation in the downswing ($p < 0.001$), face change from address to impact ($p < 0.001$) and downswing time ($p < 0.001$). According to the regression models the optimum stroke with respect to stroke direction consistency had a face rotation in the downswing of 1.6°, face change of 0° and downswing time of 325 ms. The quadratic regression model for stroke length ratio and stroke direction variability was not significant ($p = 0.13$). Regression models and equations for all four parameters are depicted in Figure 9.

Aim Performance

The elite players aimed the putter significantly left of the target ($p < 0.01$), with an average aim direction of 1.0° left ± 1.4° (Paper II). Average aim direction was also 1.0° left when short and long putts were analyzed separately. Mean aiming variability was 0.92° ± 0.25° on all putts, 0.78° ± 0.31° on short putts, and 0.82° ± 0.25° on long putts (Table 7). A linear regression analysis showed that players with higher aim deviation (less accuracy) had more variability in their aim (less precision) ($p < 0.01$) (Figure 10).

Table 7. *Putter aim direction and variability for 20 elite players, expressed as mean ± standard deviation and range in degrees (Table from Karlsen & Nilsson, 2008a)*

	All aims	Short aims (0.4 - 1.3 m)	Long aims (2.6 - 4.6 m)
Aim direction	1.0° left ± 1.4°	1.0° left ± 1.3°	1.0° left ± 1.6°
Range	4.0° left - 1.5° right	3.5° left - 1.3° right	4.5° left - 1.8° right
Aim variability	0.92 ± 0.25°	0.78 ± 0.31°	0.82 ± 0.25°
Range	0.50 - 1.37°	0.40 - 1.65°	0.49 - 1.28°

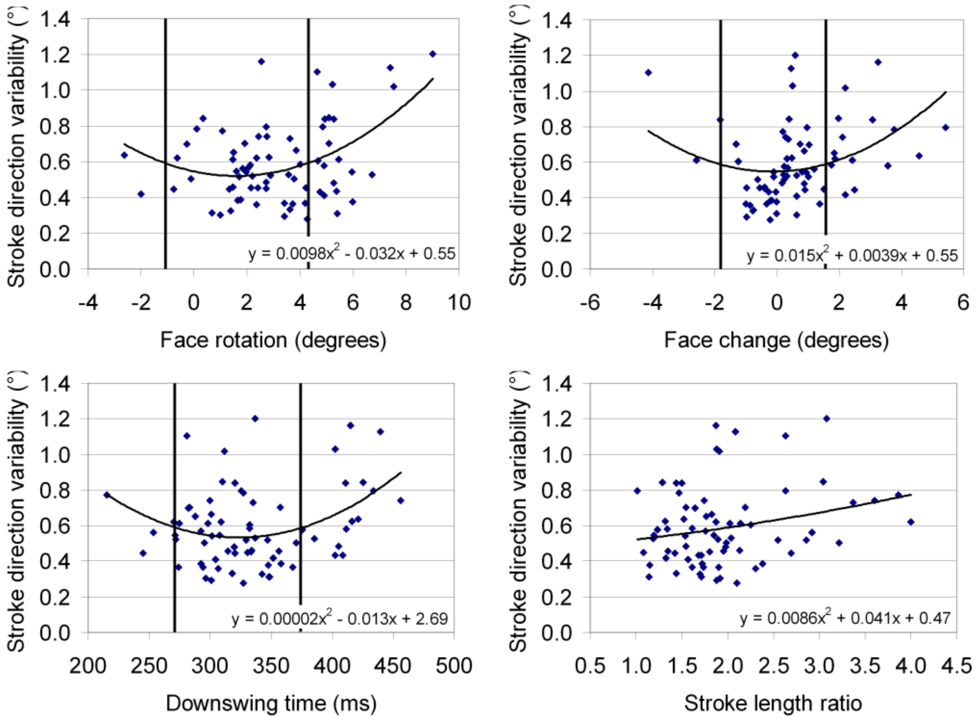

Figure 9. *How stroke direction consistency is affected by face rotation in the downswing, face change from address to impact, downswing time and stroke length ratio. The vertical lines are where the regression equation value is equal to the group average stroke direction consistency of 0.59°. Between the vertical lines, mean variability is less than average, forming an "optimal zone". Face rotation from 1° opening to 4° closing, face changes within about ±1.5° and downswing time of 270 – 370 ms are stroke strategies within the "optimal zone". Positive face rotation is the same as closing the face in the downswing. Positive face change means that the face is opened from address to impact. Regression equations and lines are included, and R^2 values are: face rotation = 0.19; face change = 0.13; downswing time = 0.13; stroke length ratio = 0.06 (Figure from Karlsen, Smith & Nilsson, 2008).*

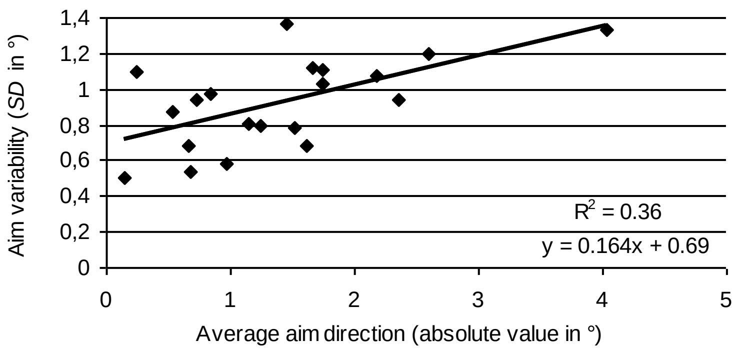

Figure 10. *The relationship between average aim deviation and aim variability. (Figure from Karlsen & Nilsson, 2008a).*

Equipment

Performance of putters with different shaft weight

The results regarding mean putting distance for putters with different shaft weights showed that the club players hit the ball further with lighter shafts (Paper IV). With the 100 g shaft the mean hitting distance was 100.2 % of the aimed distance. This is significantly longer than the 98.1 % of the aimed distance hit using a 610 g shaft ($p < 0.001$). With the 420 g shaft they hit the ball 99.3 % of the aimed distance. Despite a strong tendency, the 420 g shaft was neither significantly different from the 100 g shaft ($p = 0.08$) nor the 610 g shaft ($p = 0.02$) in putting distance. There was no significant difference between the three putters with respect to mean putting direction ($p = 0.30$) (Table 8).

Table 8. *Mean putted distance and direction with putters of different shaft weight on 4, 8 and 12 m putts (Table adapted from Karlsen & Nilsson, 2007)*

Target distance	100 g shaft	420 g shaft	610 g shaft
mean putted distance			
4 m	4.08 ± 0.17 m	4.07 ± 0.17 m	4.00 ± 0.16 m
8 m	8.02 ± 0.31 m	7.97 ± 0.36 m	7.83 ± 0.34 m
12 m	11.80 ± 0.44 m	11.60 ± 0.44 m	11.57 ± 0.56 m
All distances	100.2 %	99.3 %	98.1 %
mean putted direction			
4 m	0.37° left ± 1.09°	0.11° left ± 1.50°	0.04° right ± 1.57°
8 m	0.41° right ± 0.81°	0.25° right ± 1.23°	0.53° right ± 1.27°
12 m	0.20° right ± 0.85°	0.41° right ± 0.79°	0.38° right ± 0.86°
All distances	0.08° right ± 0.97°	0.18° right ± 1.21°	0.32° right ± 1.27°

No significant difference in accuracy among putters (100, 420 and 610 g shaft) was found when the mean deviation from the hole was analyzed on all distances ($p = 0.45$) (Table 9). In addition, there were no significant differences between the putters when distance- and direction deviation were analyzed separately ($p = 0.57$ and $p = 0.28$, respectively). Furthermore, there were no significant differences between the putters when mean deviation from putting mean ($p = 0.73$), distance variability ($p = 0.75$) and direction variability ($p = 0.94$) were used as a measure of performance (Table 9).

The ratings of "feeling of stability in the downswing", showed that the two heaviest putters were rated significantly better than the normal putter ($p < 0.01$). The normal putter (100 g shaft) was rated 55.9 ± 14.0, the medium putter (420 g shaft) 71.7 ±16.8 and the heaviest putter (620 g shaft) was rated 71.2 ± 14.9 (see scale in Table 5). All putters were rated differently on "weight feeling" ($p < 0.001$). The

Table 9. *Putting accuracy and variability for putters with different shaft weight. All results are relative mean values for 4, 8 and 12 meters combined (Table adapted from Karlsen & Nilsson, 2007)*

	100 g shaft	420 g shaft	610 g shaft
Putting accuracy			
Deviation from hole	9.2 ± 2.5 %	9.2 ± 2.9 %	9.5 ± 3.3 %
Distance deviation	8.2 ± 2.4 %	8.0 ± 3.0 %	8.4 ± 2.9 %
Direction deviation	3.0 ± 0.6 %	3.2 ± 0.9 %	3.2 ± 1.1 %
Putting variability			
Deviation from putting mean	8.4 ± 2.5 %	8.2 ± 2.7 %	8.5 ± 2.8 %
Distance variability	9.7 ± 3.1 %	9.5 ± 3.5 %	9.7 ± 3.7 %
Direction variability	3.4 ± 0.8 %	3.4 ± 1.0 %	3.4 ± 1.1 %

medium putter, and the normal putter were closest to 50 ("neither light, nor heavy"), with a mean rating of 59.1 ± 17.0 and 39.6 ± 9.1, respectively. The heavy putter was rated at 74.2 ± 11.9 on "weight feeling". The medium putter had the highest score on "overall feeling" with 69.1 ± 18.0 ($p < 0.05$). There was no significant difference between the normal putter (58.7 ± 16.5) and the heavy putter (58.3 ± 15.8) concerning overall feeling (Table 10).

Table 10. *Subjective ratings of putters with different shaft weight (Table adapted from Karlsen & Nilsson, 2007)*

	100 g shaft	420 g shaft	610 g shaft
"Weight feeling" *(0 = very light, 50 = perfect, 100 = maximum heavy)*	39.6 ± 9.1	59.1 ± 17.0	74.2 ± 11.9
"Feeling of stability in the downswing" *(0 = no stability at all, 50 = neither stable nor instable, 100 = maximum stability)*	55.9 ± 14.0	71.7 ± 16.8	71.2 ± 14.9
"Overall feeling" *(0 = extremely bad feeling, 50 = neither good nor bad feeling, 100 = extremely good feeling)*	58.7 ± 16.5	69.1 ± 18.0	58.3 ± 15.8

Aim performance of mallet and blade design putters

All targets considered together, the club players aimed blade putters (SD = 1.33°) with less variability than mallet putters (SD = 1.41°) ($p < 0.05$). The same tendency, but not statistically significant, was found when short and long targets were analyzed separately. There was no difference in average aim direction between the putter types, but there was a large difference in how the players rated aiming easiness ($p < 0.001$). Twenty-four of the thirty-two players rated the mallets easier to aim than the blade putters. For detailed results see Table 11.

Table 11. *Aim variability, aim direction and subjective ratings of aiming easiness for blade and mallet putters on all, close and distant targets (mean ± s), along with effect size(Cohen's d) and p-value (two-tailed t-test) for a comparison between the two putter types (Table from Karlsen & Nilsson, 2008b).*

	Blade putters	Mallet putters	Effect size	*p*-value
Aim variability				
All targets (0.4-4.5 m)	1.33 ± 0.49°	1.41 ± 0.54°	0.14	0.02
Close targets (0.4-1.2 m)	1.02 ± 0.50°	1.10 ± 0.41°	0.17	0.06
Distant targets (2.5-4.5 m)	1.35 ± 0.53°	1.41 ± 0.58°	0.12	0.12
Aim direction				
All targets (0.4-4.5 m)	0.8 left ± 1.8°	0.8 left ± 1.8°	0.01	0.82
Close targets (0.4-1.2 m)	0.9 left ± 1.6°	1.0 left ± 1.4°	0.03	0.65
Distant targets (2.5-4.5 m)	0.7 left ± 2.2°	0.7 left ± 2.2°	0.00	1.00
Subjective ratings (0 - 100 where 30 = difficult, 50 = average, 70 = easy)				
All targets (0.4-4.5 m)	57.0 ± 9.0	64.7 ± 9.8	0.82	0.000
Closed targets (0.4-1.2 m)	60.6 ± 10.3	68.3 ± 10.8	0.73	0.000
Distant targets (2.5-4.5 m)	53.4 ± 9.6	61.1 ± 10.5	0.76	0.001

Determinants of distance variability

Average relative distance variability for the elite players in the "40 putt test" was 10.6 % (Paper V). The factors estimated to explain distance variability were green reading (*SD* = 8.2 %), technique (*SD* = 6.3 %) and green inconsistencies (*SD* = 2.5 %). The reason why the overall relative distance variability (*SD* = 10.6 %) is less than the sum of the variabilities from the three factors is because variability from green reading, technique and green inconsistencies acts independently (in many cases a player can do two mistakes which more or less cancel out each other; e.g. underestimating how fast the ball will roll, and hitting it at lower speed than intended). The relative importance of green reading, technique and green inconsistency were 60, 34 and 6 %, respectively. (Figure 11).

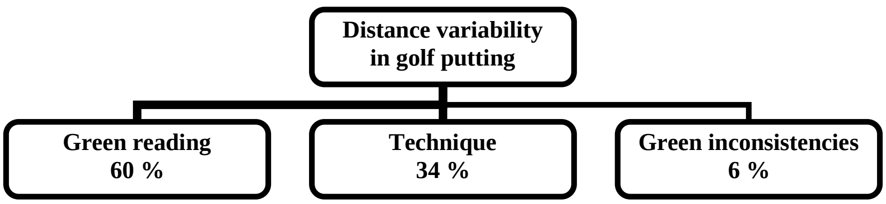

Figure 11. *A simple deterministic model presenting the relative importance of green reading, putting technique and green inconsistencies for distance variability (Figure from Karlsen & Nilsson, 2008c).*

Analysis of performance on the "40-putt test", shows that mean distance deviation on the 40 putts was related to handicap (Figure 12). In addition to the 43 players participating, another 72 highly skilled players who tested with the same methods on different occasions both indoor and outdoor, are included. Mean handicap for the 115 players was 1.8 ± 2.8 strokes.

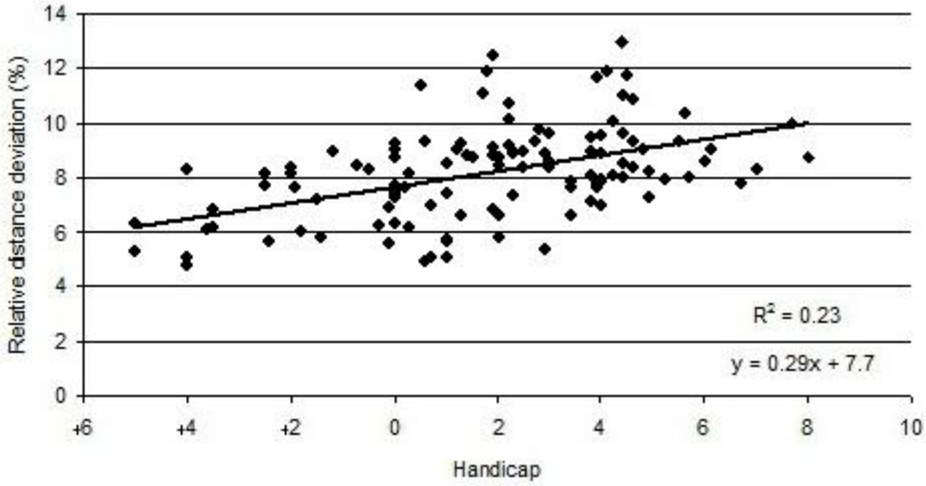

Figure 12. *The relationship between handicap and average relative distance deviation on the 40-putt test. The linear regression model equation is included (Figure adapted from Karlsen & Nilsson, 2008c).*

DISCUSSION

Technique

The quadratic regression models for face rotation, face change and downswing time (Figure 9) were all significant, indicating that there is an optimum solution for those variables regarding stroke direction consistency. These optima were face rotation of about 1.6° closing, no face change and a downswing time of 325 ms. On all three parameters there were quite large individual variations indicating that solutions different from the optima could still give high performance for some players.

The optimum club face rotation of 1.6° closing indicates that the stroke suggested by Pelz (2000) with square putter face is not optimal, but it also indicates that strokes with large face rotation in the downswing could decrease consistency. It is interesting to note that very few players kept their club face square at the end of the backswing. Out of 71 players, 69 had a significant rotation of the putter face in the downswing ($p < 0.05$), which suggests that implementation of the stroke theory proposed by Pelz (2000) is rare. The face rotation in the downswing will probably be considerably influenced by the set-up. With a forward tilted spine the rotational axis for the upper body, arms and club will be closer to horizontal and the stroke will have less putter face rotation. In contrast, a raised set-up position will give a more vertical axis of rotation and therefore more putter face rotation unless compensations are done. Therefore, the amount of putter face rotation in the downswing should always be related to the set-up position and also to the length of the backswing.

Not surprisingly, the optimum face change came out to be about 0°. It is hard to find arguments for having a face change (which means that you are not aiming at the target, or consequently miss putts to one side). Results also indicated that a small face change is acceptable regarding stroke direction consistency; probably up to about ± 1.5°.

Long downswing time negatively affected consistency for some players. An explanation might be that players with long downswing time may have spent too much time consciously controlling the motion. A more pronounced conscious control of the motion is more common in an early stage of learning a motor skill. In a skilled performance situation it may be considered more beneficial to have an automatized movement. Downswing times between 270 and 370 ms seemed to give the best overall performance. This corresponds very well with the downswing time found in 99 professional players by Marquardt (2007) of 317 ± 35 ms. Only three players in our study had shorter downswing times than 270 ms, but 16 players were slower than 370 ms, perhaps indicating that some players might benefit from a faster downswing movement.

The average stroke length ratio was 1.96, and corresponds well with Delay *et al.* (1997) and Karlsen (2003) who found stroke length ratios between 1.78 and 2.35 for elite players, and is a bit lower than Marquardt (2007) who found stroke length ratios of about 2.5 on professional players. Delay *et al*. (1997) found that low stroke length ratios were a characteristic of novice players, but in the present study stroke length ratio had no effect on stroke direction consistency, even though 24 %

of the players had "low" stroke length ratios between 1 and 1.5. These players are characterized by using the same strategy as the novices in Delay *et al.* (1997) and they also follow the recommendation of Pelz (2000) with a stroke length ratio of 1.2. One may ask why most elite players incorporate much higher stroke length ratios than novices if stroke length ratio does not affect performance. A possibility is that it affects club head speed consistency, but the post-hoc analysis did not show any effect of different stroke length ratios. A more likely explanation might be the high focus in the putting teaching literature on having positive acceleration at impact (e.g. DeGunther, 1996; Sörenstam, 2007; Mickelson, 2009). This focus might have affected some elite players to increase their stroke length ratio unnecessarily.

Aim

Methodological considerations

The angular position for each of the targets was carefully measured both with the help of 3D-kinematic system and geometrically, with help of an angle and a distance ruler. The mean difference between the 16 angular target positions comparing the "3D-method" and the "geometrical method" was 0.28°, with the largest difference for a single target being 0.65°. The differences were mostly caused by a minor systematic linear underestimating of the angles by the 3D-system which equaled 0.4° at 60° away from the calibration line. The 3D-system was used for both aim testing and angular positioning of the targets. The average aim variability (expressed as *SD*) over seven series of 16 aims, when aiming aided by a thread towards the target (3D-method, Figure 13), was 0.19°. However, due to human errors in positioning the putter to the thread, the actual variability of the test method had to be somewhat lower than 0.19°. Anyway, this is far below the variability of the best elite players, which have an aim variability of about 0.5°, so the accuracy of the aim measurements was considered sufficient to determine the aiming skills of elite players.

Figure 13. *Illustration of how the aim test was done with help of a thread ("3D-method"). This method had a aim variability (expressed as SD) of 0.19°.*

The method used in the present study to record the aiming of the elite player is reliable and relatively fast. It has opened up for the possibility to discover different complex aiming patterns, and is also more valid than earlier methods, because different targets are used. A disadvantage is that the calibration routine requires an experienced test leader, who is able to consistently place different putters square to a straight line. To reduce the possibility of erroneous calibrations we demanded that the player controlled the calibration as well. Disagreements between the test leader and the player about the calibration were rare, which indicate that the calibration errors probably were small.

Measuring aim while putting golf balls could also be inaccurate. Often a player might correct a miss hit putt with a change in aim, and aiming variability might increase because of a bad stroke. Therefore, we consider measuring aim without hitting golf balls as a better strategy.

Elite player performance

The elite players aimed systematically to the left by 1.0°, which corresponds closely to the change in face angle from address to impact of 0.6° opening found by the 71 elite players in Paper I. This is in contrast to the data of Marquardt (2007) where 99 PGA-Tour players on average aimed 0.35° to the right, with an average change in face angle from address to impact of 0.05° closing. It is also contradictory to MacKay (2008) who found that 77 % of senior club players aimed right of the target. It seems that the aim strategy of younger elite players were different than for older club players. One hypothesis might be that this comes from the full swing where older players often have less upper body rotation when using an arm dominant swing. According to our observations, these senior swings typically have an outside in swing path where the players need to aim right in order to start the ball on the target line. However, this needs to be further investigated.

The further away the average aim direction was from the target, the higher the aim variability was according to the regression model. This indicates that it is beneficial to avoid Compensations where, for example, a player aims left and opens the club face throughout the stroke to impact. The latter corresponds well with the finding from Paper I where stroke direction variability increased with larger changes in face angle from address to impact.

Comparing the importance of different factors for direction variability

In Paper I, II and III questions related to directional aspects of putting such as green reading, putter aim and technique were investigated. A relevant topic for the practical field is the importance of the different factors in comparison to each other. This idea will be addressed in the following section.

Initial ball start direction

According to the regression analysis in Paper I a scratch player has a directional variability of 0.54° caused by the stroke. Similarly, a scratch player has an aim direction variability of 0.92°. This indicates that putter head aim is a much larger source of direction variability than the putting stroke. However, the conditions during data collections may have affected the result. The data of the technique study were recorded on repeated putts to the same target, while the aim data were recorded on aims to different targets. If technique data were collected on putts to different targets, stroke direction variability may have increased. Both studies were done in lab situations, although some of the technique data were collected outdoor. Both situations are different from a tournament situation, but investigating these problems situation posed large logistical and methodological challenges, and is not possible with present technology.

Marquardt and Fischer (2008) described the yips as being a major problem for those players affected, especially for direction on short putts. Choking could possibly also lead to acute technical deterioration in a tournament situation. Choking can be defined as "performing more poorly than expected given one's skill level" (Beilock & Gray, 2007), and can be shown as an inward directed attention under pressure leading to a disrupted and less smoothly technique also called "dechunking" (Masters, 1992). Yips and choking will most often occur in a mentally high-pressure tournament situation, and thus this may present a possible error source underestimating the stroke direction variability in our study. However, we experienced that the data collection situation with advanced equipment was perceived quite threatening by some players as well. This indicates that the difference between the data collection and a tournament situation anyhow could be relatively small.

Regarding aim, some arguments suggests higher variability in a tournament situation compared to a lab research situation. First, the visual appearance of a putting green seems more complex than for an indoor putting mat. Outdoor, there will be shadows, cut lines, undulations and more variation in light conditions than indoors. A tournament situation could possibly affect cognitive skills like aiming through a perceptual narrowing induced by severe stress, a process which Gladwell (2000) have termed "panicking". However, practical experience from teaching, testing and coaching elite players indicates that the difference in aim from lab situations to outdoor greens is small.

Although difficult to quantify, a reasonable assumption is that aim remains a greater source of direction variability than technique, if those two variables were to be compared in a tournament situation.

Looking further at the different components of stroke direction, face angle was by far the most important one. This is because face angle mechanically affects the initial ball start direction much more than putter path (83 vs. 17 %, Pelz 2000). Bearing in mind that stroke variability has little influence on direction variability compared to aiming and green reading, improvement of putter path and horizontal impact point consistency has very little influence on putt direction consistency. This standpoint is confirmed by the knowledge of the putter path variability (expressed as *SD*) of an average European Tour player (which according to our results is 0.7°). Based on this we can calculate that he only will miss about 1 % of all putts from 10 metres, keeping everything else than the putter path perfect. In elite tournament play, the same players actually miss about 93 % of putts from 10 metres (Tierney & Coop, 1998).

Inconsistencies of the green

Another source causing variability in the direction of a putt is the inconsistencies of the green surface. Pelz (1989) investigated green inconsistencies using the TrueRoller™ on 12’ (3.7 m) putts. Depending on the condition of the green and time on the day of play, he was able to hole from 30 - 84 % of putts. Assuming that direction errors caused by the green are normally distributed around the hole, and that the effective hole diameter in Pelz’s study was 100 mm (actual hole diameter is 108 mm, but depending on the approach speed of the ball, the effective hole diameter will be less), that corresponds to a direction variability between 0.6° and 2.0° caused by inconsistencies of the green. Direction variability caused by green irregularities was also measured in Paper V (although not reported). We found a variability of 1.0° after rolling 20 putts from the same spot with a True Roller™ an average distance of 8.9 m. This result corresponds well with the data reported by Pelz (1989).

According to Pelz (1989) and our data from Paper V, it seems that a good green will cause a direction variability probably a little less than 1°. This is about the variability caused by aiming (0.92°) and a bit more than the variability caused by technique (0.54°). For comparison, this means that the inconsistencies of the green are a larger source of direction variability than the technique of the elite golfer. However, as shown by Pelz (1989), there could be large variations between different greens and also throughout a tournament on the same green.

The importance of green reading for direction

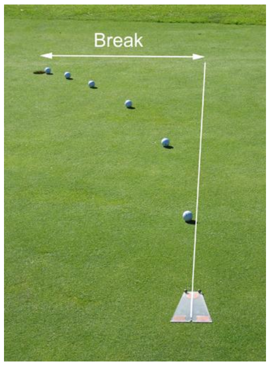

Figure 14. *Illustration of how “break” was measured*

Ideally we should measure the variability in reading greens for direction directly. However this is quite complicated methodologically. In pilot studies we have set up various putts where players are asked to indicate the amount of break to be played. In this case break is measured as the distance from the center of the hole to the point in the direction of the initial ball direction line beside the hole (Figure 14). Theoretically the green reading performance (direction) of a player could be measured by comparing the reported break with the true break measured out with help of a ball rolling device. However, there are different ways to read greens. Many players try to visualize the path the ball will roll over to the hole, and the path is their decision. Other players translates the path into an initial start line where they either aim the ball with a line on it, find an intermediate target typically 50 cm in front of the ball or choose a target beside the hole (as they were asked to do in the pilot study). Yet, a few players neither try to visualize the ball path, nor do they pick any aim points. These players only look at the undulations on the green and act very intuitively on what they see. This means that forcing all players into reporting the amount of break into something easily measurable is very difficult. Quite a few players reported in the pilot studies that it was difficult to pick a point, because they were uncommon to this methodology of reading break. Therefore it is difficult to measure green reading skills directly. In addition, the amount of break will vary, depending on the intended approach speed of the ball into the hole. Yet another issue is that it could be difficult to determine the correct break by rolling several balls from the same spot, since there are inconsistencies in the green itself, and since rolling several golf balls from the same spot can make tracks in the green affecting the ball roll.

Since the direct measurement of green reading skills (for direction) was difficult, we chose to use an indirect measure to estimate the variability in direction caused by green reading. Assuming that variability in aim, stroke, green inconsistencies and green reading act independently, the total direction variability can be calculated according to DeMuth (2006) by the following equation:

Eq. 1. $$SD_{greenreading} = \sqrt{SD^2{}_{totaldirection} - \left(SD^2{}_{aim} + SD^2{}_{stroke} + SD^2{}_{greenincons.}\right)}$$

Based on putting tests (about 6000 short putts) carried out among national players in Norway in 2009, a scratch player holes about 28.7 % of 3.7 meter putts in tests of various putts (same distance as Pelz used to test green inconsistencies) (Table 1). Assuming an effective hole diameter of 100 mm (actual hole diameter = 108 mm), and normally distributed direction that equals an direction variability of 2.10°. Inserting this into the equation together with aim variability of 0.92°, stroke variability of 0.54° and green surface variability of 0.8°[2] the direction variability for a scratch player caused by green reading ($SD_{greenreading}$) can be estimated to:

Eq. 2: $$SD_{greenreading} = \sqrt{2.10^2 - \left(0.92^2 + 0.54^2 + 0.80^2\right)} = \underline{1.62°}$$

A more conservative estimate of the importance of green reading assumes that the players perform aim and technique 20 % more variable in a tournament situation, with aim variability of 1.1° and stroke variability of 0.65°. Also assuming inconsistent greens causing direction variability of 0°, and that the scratch players still manage to hole 28.7 % of 3.7 meter putts in tournaments, would give an estimate of direction variability caused by green reading of:

---

[2] *In Paper V we measured direction variability caused by green inconsistencies to 1.0°. Subjectively the green used in Paper V was more inconsistent than the average of greens used to test national players (Table 1). Therefore it is a reasonable to set green surface variability in this calculation (Eq. 2) to 0.8°.*

Eq. 3. $SD_{greenreading} = \sqrt{2.10^2 - \left(1.1^2 + 0.65^2 + 1.0^2\right)}$ = <u>1.33°</u>

However, it must be noted that these estimates (Eq. 2. & Eq. 3) do not take into consideration misses on 3.7 meter putts caused by distance errors, other than adjusting the effective hole size from 108 to 100 mm.

The above estimates of direction variability caused by green reading should be used with caution, since variables included have some uncertainties. Additionally, the measurements of inconsistencies caused by green irregularities present methodological challenges because the green surface possibly could be altered by rolling several balls from the same spot. Also, the assumption that variability in green reading, aim and stroke are independent may be questioned. However, if there are any dependencies between the variability of aim and stroke, it is reasonable to assume that it there exists a positive interaction, meaning that erroneous aim is corrected by the stroke. If so, this indicates that direction variability caused by green reading is larger than estimated in Eq 2. and Eq. 3.

The value of knowing the importance of green reading in determining direction variability is very high from a practical perspective, and thus the estimate mentioned above can be justified as long as it is used with caution. Both estimates (Eq. 2 & Eq. 3) indicate that green reading is the most important factor for direction variability, and according to Eq. 1, green reading could possibly be far more important than aim, technique and green inconsistencies. So, in conclusion, it seems likely that green reading is the most important factor for direction variability, followed by aim and green inconsistencies. Technique is the least important factor of those four. However, in line with Nicholls (2007) and Marquardt (2009), it is reasonable to assume that technique variability could increase quite much in a tournament situations for players disposed for choking or yips.

Equipment

Methodological considerations

Contradictory to most earlier research on aim performance (Table 2) we are convinced that precision (consistency) is the primary performance measure for aiming. Our experience from coaching is that accuracy is relatively easy to improve while aiming precision takes longer to develop. This is supported by post-hoc linear regression analysis of the present data which shows that average aim deviation from the targets (accuracy) not related to handicap (p = 0.64), yet low handicappers were more precise ($p < 0.05$).

Aim design

The major finding from this study was the discrepancy between perception of aiming easiness and aim performance. Thus, even though the club players rated mallet putters easier to aim with than blade putters, they actually aimed better using blade putters. It is likely that the strategy when aiming a blade putter is to visualize an imaginary line perpendicular out from the putter face. This is probably the most likely available strategy with irons and woods as well. A mallet type putter though invites an aiming strategy where the aiming aid (e.g. the aim line) can be visualized directly towards the target. This might intuitively look easy, but if we take all clubs in the bag into account golf players probably have much more experience seeing an aim line extending perpendicularly out of a club face. This may be an explanation of the discrepancy between perception of performance and actual performance. Thus, by using mallet type putters the players need to switch between two strategies instead of using one predominant aiming strategy for all clubs. Presumably, extensive training will reduce the variability that might be related to this switch in aiming strategy. Another possible explanation might be that the marketing of the mallet putters aiming advantage has affected the participants.

Results from the present study only apply to a "feeling aim strategy". With an aiming strategy where the ball is marked with a line which is directed towards the target, the key in putter design would be to have a putter which is easy to set-up perpendicular to the line on the ball. In such case a different type of putter head design might be advantageous for aiming performance.

Shaft weight

The results showed that players hit the ball significantly shorter with heavier shafts, even though they were aiming at the same target and had feedback from each shot, which made it possible to correct the distance during the series of ten putts. This corroborates the findings from Nilsen (2008). The weight of the shaft has little influence on the initial ball speed for a given club head speed (unpublished data). Therefore, shorter putting with heavier shafts may be caused by the fact that a greater force had to be applied to the heavier putter to reach the same club head speed, and the same putting distance as with a light putter. Getting accustomed to applying a greater force for a given distance probably takes some time, especially if a player is unaware that he/she needs the same club head speed with a heavy shaft in order to hit the ball the same distance.

In general, the players rated the medium weight putter (420 g shaft) as best. It had a significantly better rating than the two other putters on "overall feeling", a better rating than the normal putter on "feeling of stability in the downswing" and a better rating than the heaviest putter on "weight feeling". Although the players rated the medium weighted putter as best, this was not supported by the results from the performance test. There were no significant differences among any of the putters in any of the performance measures. Taken into consideration that none of the players had ever tried a putter with heavy shaft before the day of testing, and that their mean playing experience with a normal putter was 8.4 years, the result for the medium weighted putter may show in a longer time perspective that heavier shafts than today's normal may be advantageous to use. This is supported by Nilsen (2008) who found better accuracy with heavier putter shafts among highly skilled players.

The results may explain how heavy the putter shaft should be. The heaviest putter (610 g shaft) had a mean rating of 74.2 on “weight feeling” which was a bit heavier than the rating of heavy (70 in the rating scale). Only one of the 24 players rated it as the perfect weight, all the others rated it as more or less too heavy. This indicates that there is a limit on how heavy the shaft could be before it feels awkward for a person with a given muscle strength, and that the 610 g shaft probably is near or over that limit for many players. This may be explained by the large momentum created by the heavy shaft, which again makes a large rotational moment at the wrists, especially in the downswing where acceleration is at the highest (Karlsen, 2003).

If the aim of putter manufacturing was to find a shaft weight that suits as many players as possible, subjective ratings indicates that it should be somewhere between the “normal” and the “medium” shaft, around 250 – 300 g. Similarly, Nilsen (2008) found that 20 highly skilled players rated 290 g as the ideal shaft weight with a 292 g putter head. We have to be aware that shaft weight has to be considered together with club head weight. With higher or lower club head weights than normal, other shaft weights may be preferred. We also have to take into account that variations in individual preferences known from the putter shaft weight study are quite large.

The importance of equipment

Except from a small difference in performance showing that club players aimed slightly better with blade putters than with mallet putters, no differences in accuracy between putters were found in the two studies of shaft weight and putter head design. Nilsson and Karlsen (2006) found that a wing type putter performed better than both a blade and a mallet type putter on off-center hits. However, results from the 3D-kinematic analysis of elite players (Paper I) showed an impact point variability of only 2.7 mm in toe-heel direction. Horizontal impact point variability has very little influence on direction variability. This indicates that there only will be a negligible improvement in the putting direction variability of an elite player if he changed to a more forgiving putter. This is same conclusion Werner and Grieg (2000) reached when they investigated the effect of putter design on horizontal off-center hit performance.

Although only some variables of putter design have been investigated, it seems that putter design had relatively little effect on performance, especially when we bear in mind that technique seems to have a much smaller effect on performance than green reading. This is in line with the findings of Nilsen (2008) who analyzed the technique of elite golfers using putter shafts of various weights. Nilsen found very few differences in putter head kinematics even though the players used putter shafts with a large variation in weight (144 - 611 g).

However, there are reasons why elite players still should focus on finding a good putter. If there is a positive effect of changing to a different putter, such a change can be achieved quite easily, and without long periods of training. In addition, post-hoc analysis shows that even if two types of putter design show a relatively similar performance, there might be differences at an individual level. One example from the putter aim design study was a player who on average had aim variability of 0.77° (range: 0.70 - 0.86°) with the six blade putters and 1.03° with the six mallet putters (range: 0.90 - 1.13°). This particular player was re-tested with the same schedule two days later, and even on the re-test the blade putters were clearly better (blades: 0.63°, range 0.51 - 0.73° & mallets: 0.80°, range 0.69 - 0.85°).

Distance control

Distance performance in putting is decided by distance variability (precision) and systematic errors (accuracy). An analogy to this is rifle shooting. A shooter can have very little variability (all shots end up at the same place), but if they are all to the right the score will not be good. Similar to the findings regarding putter aim, coaching experience shows that distance accuracy is easier to adjust than precision.

Distance variability

Paper V addressed the components of distance variability. In contrast to what we perceive from instructional articles and elite players practice schedules, green reading seemed to be much more important for distance variability (60 %) than the technique performance (34 %) and the inconsistencies of the green (6 %). Although the results were reported in exact percentages, those numbers should be used with caution. The calculations were based on several assumptions, and the reported numbers came from a calculation conservatively estimating the importance of green reading for distance variability. No research has systematically investigated the way green reading and green speed should be taught not how best to evaluate the interactions between them. In contrast there have been several studies regarding putting technique (e.g. Delay *et al.* 1997; Marquardt. *2007*), and we also find the knowledge about technique being relatively good among coaches. This may also be seen in the abundant instruction literature on the swing technique in golf, including putting.

Systematic errors

Systematic distance errors in putting have not been reported before. Neither was systematic errors addressed initially in Paper V, but post-hoc analysis of the data revealed some interesting findings. Forty-six players hit 40 different putts in seven different fields. For analysis we picked out the first putt which was hit in two opposite fields going up and down a tier (Figure 15). The down-tier putt was 14.90 m and the average putted distance by the 46 players on the first attempt was 15.78 m (105.9 ± 9.0 %). Average putted distance for the corresponding uphill putt, which was 14.10 m, was 13.01 m (92.3 ± 13.7 %). This indicates that elite players underestimate the effect tiers have on ball roll.

Figure 15. *Picture of the practice green from Paper V. (1) Start spot for the up-tier putt. (2) Target line for the up-tier putt. (3) Start spot for the down-tier putt (4) Target line for the down-tier putt.*

Another finding from the same study was that the longer the putt was, the shorter the players putted in percentage of the putting distance (p < 0.05) (Figure 16). This indicates that elite players also underestimated the effect changes in distance had on how hard they needed to put the ball. The above findings show a trend that elite players underestimate some variables, the effect of tiers on roll distance, and the effect of changes in putt distance. There is also anecdotal evidence that elite players systematically underestimate the effect of changes in green speed. Typically when arriving at a new course where the greens are faster than they are used to, the tendency is to put too far, and the opposite if they come to slower greens. Although more research needs to be done to verify these findings, it seems that systematic errors in putting might influence the score even for highly skilled players.

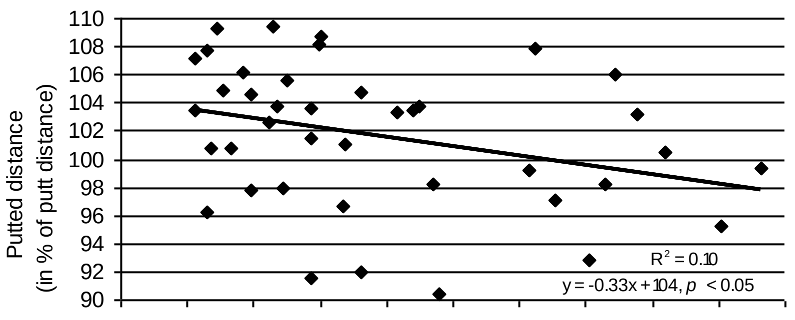

Figure 16. *The relationship between target distance and actually putted distance. Each data point represents the mean of 46 highly skilled players.*

Mental aspects of putting

Mental aspects of performing on elite level in putting have not been directly investigated in the present thesis. However, other research studies indicate that the mental part of putting has a major impact on performance. Mental factors can affect putting performance on different levels in the performance model presented in Figure 1.

As discussed by Marquardt (2009) yips can be detrimental to performance. The majority of players suffering from yips tend to be professionals and low handicap players, and it is a general consensus that the yips tend to manifest under mental pressure situations where the player is likely to feel anxious (Kingston, Madill & Mullen, 2002; Smith, Adler & Crews, 2003). The yips is often kinematically shown as a drastically impaired control of the putter face angle (Marquardt, 2009). This underlines the importance of being able to cope with stressful tournament situations, and is in line with Nicholls (2007) who found that putting was among the most frequently reported stressors by Scottish international amateurs.

Beauchamp (1998) did in-depth interviews with experienced PGA Tour Golfers, and concluded that the ability to see and feel the line (positive imagery), and to use task focus in the pre-shot routine were critical psychological skills contributing to peak putting performance. The present thesis, which has shown that green reading ability is very important for putting performance, is supporting the conclusion from Beauchamp, since green reading is closely related to the ability to focus in the pre-shot routine. Stressful situations in golf do not only affect motor performance but also more cognitive skills like e.g. green reading or aiming. Clark, Tofler and Lardon (2005) call this process for panicking, and describe this as a perceptual narrowing, or “the mind going blank”, and it affects decision making which relies on implicit memory.

Although psychological factors clearly may affect performance in putting, it is difficult to quantify the importance and compare it with the importance of more technical skills like stroking a putt with correct direction and speed.

CONCLUSIONS

The main conclusions from the present thesis are summarized below:

- The direction variability of elite players putting technique was very low, with mean value for scratch players of 0.54°.
- Optimum technique zones for stroke direction consistency were: face change = 0 ± 1.5°, downswing time to impact = 270 - 370 ms, face rotation in downswing to impact = 1° opening to 4° closing, but there are probably quite large tolerance for individual adjustments.
- A method to measure aim performance was developed and validated, and considered better than methods from previous research publications.
- Average aim variability for a scratch player was 0.92°, and elite players aim left of the target ($p < 0.01$) by an average of 1.0°.
- Green reading is considered the most important factor for direction consistency, followed by putter aim and green inconsistencies. Technique is considered the least important unless a player is disposed for yips or choking. Methodological challenges give these results some uncertainty.
- Club players rate mallet design putters easier to aim with than blade putters ($p < 0.001$), while they actually aim more consistent with blade putters (*SD* = 1.33° & 1.41°, respectively, $p < 0.05$).
- There is no difference in accuracy when comparing putters with shaft weight of 100, 420 and 610 g, but club players puts slightly longer with lighter shafts ($p < 0.05$). About 250 - 300 g were rated as preferred shaft weight, when combined with a putter head weight of 310 g.
- Green reading (60 %) is considered more important for distance variability than technique (34 %) and green inconsistencies (6 %). Methodological challenges give these results some uncertainty.

Practical applications

Results from this thesis apply to players, coaches and putter manufacturers. The main suggestion is that green reading practice should be highly prioritized, and technical practice should be given less priority. Most players have a highly direction consistent putting stroke in a test situation, so the main issue is probably to be able to perform in a tournament situation, and not to improve the consistency of the technique further in practice. Baumeister (1984) defined pressure as “any factor or combination of factors that increases the importance of performing well on a particular occasion”. The knowledge of how little important the stroke is for direction consistency can actually help to relieve the pressure from short putts in tournament situations, and reduce the frequency of yips and choking for disposed players.

Taking focus away from putter path and impact point training, which has little potential of improving performance could possibly also have psychological benefits. Masters, Polman and Hammond (1993) found that individuals who often try to "reinvest" their technique will be more exposed to dechunking. As an example, reinvestment in golf could be a player who in a tournament situation tries to recall swing keys in order to "control" the technique performance. If players in first case have less technical swing keys e.g. on the putter path, the chance of reinvestment would most likely decrease.

Another suggestion is that a random practice schedule could be preferable over a blocked practice schedule for green reading practice. Green reading is a cognitive process where the players have to create an action plan for the motor performance based on the input they get from the green read. In random practice players need to focus more on green reading because they are challenged with a new situation for each trial. This demands that they need to create a new action plan which in turn may lead to stronger memory representation of the skill resulting in an enhanced learning (Immink & Wright, 2001). A blocked practice schedule might not be equally beneficial because players can correct the speed and direction of each putt according to the result of the previous putts. This is supported by researchers which have found random practice schedules to be beneficial over blocked schedules for putting among good players (Goodwin & Meeuwsen, 1996; Guadagnoli, Holcomb & Weber, 1999; Hwang, 2003).

Another application is to focus less on the equipment. It is perceived that many players blame missed putts and bad putting on the equipment, and thus try to fix this by changing putter. Findings in this thesis indicates that the equipment most likely have little influence on performance. However, a thorough putter fitting on individual basis is anyway recommended because it might show that a certain weight or certain putter head designs might perform better. A heavier putter shaft was preferred by many players, and could be recommended to try. Since players systematically putted shorter with heavier shafts, it could especially be recommended to try for those playing on faster greens or if they often putt too far. In addition more traditional putter fitting parameters like length, lie, loft and grip should not be forgotten.

The distance control study revealed systematic errors often occurring among elite players like putting short on longer and up-tier putts and putting long on down-tier putts. In addition Pelz (1994) have earlier shown that elite players severely underestimate the break. Awareness is advised, and systematic game analysis could possibly help elite players to discover any systematic error in their putting and thus reducing the score by correcting them.

Future directions for putting performance research

Putting is a complex skill and knowledge from many academic fields should be combined to understand elite performance. Present research status is that the majority of studies have focused on technique, aim, equipment and motor learning aspects. Few studies have focused on green reading, the pre-shot routine and mental aspects, which seem to be of most importance for putting performance. The pre-shot routine can be seen to have two purposes; reading the green and mentally prepare for the shot. How green reading and mental preparation best can be integrated in the pre-shot routine is one area of high importance for future research.

Another related area is aiming strategies. Over the last decade it has become popular to align the ball towards the target with a line on it. This is together with traditional "feeling aim" and aim with an intermediate target the three most common aiming strategies. Finding out which strategy that is most effective for aiming, and also easiest to implement in the pre-shot routine is an important question which has not been investigated.

Performance peaking of distance control foremost but also direction control is another unexplored area. Both professionals and amateurs play a high number of tournaments under different green conditions throughout a year. Often they only have 1 - 2 days to prepare on the tournament course. Coaching experience has shown that players are unprepared when tournaments start. Distance control adjustments can especially be difficult if there are large differences in green speed between the tournament course and where they have played the previous week. How and how much a player need to practice and prepare in such situations is another area for future research.

Regarding technique and putter aim research 3D-analysis systems and force plates have advanced the research the last decade. However, most 3D-analysis have focused on putter head kinematics (e.g. Delay *et al*. 1997; Marquardt, 2007 & the present thesis). A further advance in putting technique research is to relate more common teaching parameters like grip, spine configuration, eye position, ball position shoulder external rotation, weight distribution to technique and aim consistency.

The present thesis has not compared the importance of direction control and distance control for performance. Knowledge about this would also be important to make priorities in training, and is also a topic for future research.

REFERENCES

Alexander, D. L., Kern, W. (2005). Drive for show and putt for dough? *Journal of Sports Economics, 6*, 1, 46 - 60.

Baumeister, R. F. (1984). Choking under pressure: Self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of Personality and Social Psychology, 46*, 3, 610 - 620.

Beauchamp, P. H. (1998). Peak putting performance: Psychological skills and strategies utilized by PGA Tour golfers. In, M. R. Farrally & A. J. Cochran (Eds.), *Science and Golf III: Proceedings of the World Scientific Congress of Golf,* 181 - 189. Champaign, IL, Human Kinetics.

Beilock, S. L. & Gray, R. (2007). Why do athletes choke under pressure? In, G. Tenenbaum & R. C. Eklund (Eds.). *Handbook of Sport Psychology, 3rd ed.,* 425 - 444, Hoboke, NJ, John Wiley & Sons.

Brooks, R. J. (2002). Is it a pendulum or is it a plane? Mathematical models of putting. In, E. Thain (Ed.), *Science and Golf IV: Proceedings of the World Scientific Congress of Golf*, 127 - 141. London, Routledge.

Brouliette, M. & Valade, G. (2008). The effect of putter face grooves on the incipient rolling motion of a golf ball. In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf*, 363 - 368. Mesa, AZ, Energy in Motion.

Carnahan J. V. (2002). Experimental study of effects of distance slope and break on putting performance for active golfers. In, E. Thain (Ed.) *Science and Golf IV, Proceedings of the World Scientific Congress of Golf*, 113 - 126. London, Routledge.

Clark, T. P., Tofler, I. R. & Lardon, M. T. (2005). The sport psychiatrist and golf. *Clinics in Sports Medicine, 24*, 959 - 971.

Coello, Y., Delay, D., Nougier, V. & Orliaguet, J.-P. (2000). Temporal control of impact movement: The time from departure control hypothesis in golf putting. *Int J Sport Psychol*, 31, 24 - 46.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ, Erlbaum.

Craig, C.M., Delay, D., Grealy, M.A. & Lee, D.N. (2000). Guiding the swing in golf putting. *Nature*, 405, 295 - 296.

DeGunther, R. (1996). *The art and science of putting*. Chicago, Masters Press.

Delay, D., Nougier, V., Orliaguet, J.-P., & Coello, Y. (1997). Movement control in golf putting. *Human Movement Science, 16,* 597 - 619.

De Muth, J. E. (2006). *Basic Statistics and Pharmaceutical Statistical Applications*. New York, CRC Press.

Douglas, K. & Fox, K. R. (2002). Performance and practice of elite women European Tour golfers during a pressure and a non-pressure putting situation. In, E. Thain (Ed.) *Science and Golf IV, Proceedings of the World Scientific Congress of Golf,* 246 - 256. London, Routledge.

Farrally, M. R., Cochran, A. J., Crews, D. J., Hurdzan, M. J., Price, R. J., Snow, J. T. and Thomas, P. R. (2003). Golf science research at the beginning of the twenty-first century. *J. Sports Sciences, 21,* 753 - 765.

Gladwell, M. (2000). The art of failure. *The New Yorker, 21,* 84 - 92.

Goodwin, J. E., & Meeuwsen, H. J. (1996). Investigation of the contextual interference effect in the manipulation of the motor parameter of over-all force. *Perceptual and Motor Skills, 83*, 3, 735 - 743.

Guadagnoli, M. A., Holcomb, W. R. & Weber, T. J. (1999). The relationship between contextual interference effects and performer expertise on the learning of a putting task. *Journal of Human Movement Studies, 37*, 1, 19 - 36.

Gwyn, R. G., Ormond, F. & Patch, C. E. (1996). Comparing putters with a conventional blade and cylindrically shaped club head. *Perceptual and Motor Skills, 82,* 31 - 34.

Gwyn, R. G., & Patch, C. E. (1993). Comparing two putting styles for putting accuracy. *Perceptual and Motor Skills, 76,* 387 - 390.

Hoadley, B. (1994). How to lower your putting score without improving. In, A. J. Cochran & M. Farrally (Eds.) *Science and Golf II: Proceedings from the World Scientific Congress of Golf,* 186 - 192. London, Routledge.

Hurrion P. (2009). A biomechanical investigation into weight distribution and kinematic parameters. In, S. Jenkins (Ed.) *Annual Review of Golf Coaching 2009,* 89 - 99. Brentwood, UK, Multi-Science Publishing.

Hwang, G-Y. (2003). An examination of the impact of introducing greater contextual interference during practice on learning to golf putt. *Part of doctoral thesis at Texas A&M University*, College Station, Texas.

Immink, M. A. & Wright, D. L. (2001). Motor programming during practice conditions high and low in contextual interference. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 2, 423 - 437.

Karlsen, J. (2003). Golf Putting: An analysis of elite-players technique and performance. *Master thesis from The Norwegian University of Sport and Physical Education*, Oslo, Norway.

Kingston, K., Madill, M. & Mullen, R. (2002). Yielding to internal performance stress? - The yips in golf: A review with a commentary from a players perspective, In E. Thain (Ed.), *Science and Golf IV: Proceedings of the World Scientific Congress of Golf, 268 - 283.* London, Routledge.

Koslow, R. & Wenos, D. (1998). Realistic expectations on the putting green: within and between days trueness of roll. *Perceptual and Motor Skills, 87,* 1441 - 1442.

Lee, T. D., Ishikura, T., Kegel, S. Gonzales, D. & Passmore, S. (2008). Head-putter coordination patterns in expert and less skilled golfers. *Journal of Motor Behaviour, 40*, 4, 267 - 272.

MacKay, J. (2008). An analysis of eye and club face alignment at address in putting. In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf*, 202 - 207. Mesa, AZ, Energy in Motion.

MacKenzie, S. J. & Sprigins, E. J. (2005). Evaluation of the plumb-bob method for reading greens in putting. *Journal of Sports Sciences*, *23*, 1, 81 - 87.

Marquardt, C. (2007). The SAM PuttLab: Concept and PGA Tour data. In, S. Jenkins (Ed.) *Annual Review of Golf Coaching 2007*, 101 - 120. Brentwood, UK, Multi-Science Publishing.

Marquardt, C. & Fischer, M. (2008). Movement kinematics of the golfer's "yips", *In, D. Crews & R. Lutz (Eds.), Science and Golf V: Proceedings of the World Scientific Congress of Golf,* 216 - 223. Mesa, AZ, Energy in Motion.

Marquardt, C. (2009). The Vicious Circle Involved in the development of the yips. In, S. Jenkins (Ed.) *Annual Review of Golf Coaching 2009*, 67 - 78. Brentwood, UK, Multi-Science Publishing.

Masters, R. S. W. (1992). Knowledge, nerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology, 83,* 343 - 358.

Masters, R. S. W., Polman, R. C. J. & Hammond, N. V. (1993). “Reinvestment”: a dimension of personality implicated in skill breakdown under pressure. *Personality and Individual Differences, 14*, 655 - 666.

McDaniel, K. D., Cummings, J. L. & Shain, S. (1989). The “yips”: a focal dystonia of golfers. *Neurology*, *39*, 192 - 195.

McGlynn, F. G., Jones, R. & Kerwin, D. G. (1990). A laser based putting alignment test. In, A. J. Cochran (Ed.), *Science and golf I: Proceedings of the First World Scientific Congress of Golf*, 70 - 75. London, E. & F.N. Spon.

Mickelson, P. (2009). *Secrets of the short game*. New York, Harper Collins.

Neale, D. C. & Andersson, B. D. (1966). Accuracy of aim with conventional and croquet-style putters. *The Research Quart., 37*, 87 - 94.

Nicholls, A. R. (2007). A longitudinal phenomenological analysis of coping effectiveness among Scottish international adolescent players. *European Journal of Sport Science, 7,* 3, 169 - 178.

Nicholls, A. R., Holt, N. L., Polman, R. C. J & James, D. W. G. (2005*a*). Stress and coping among international adolescent golfers. *Journal of Applied Sport Psychology, 17,* 333 - 340.

Nicholls, A. R.; Holt, N. L. & Polman, R. C. J. (2005*b*). A phenomenological analysis of coping effectiveness in golf. *The Sport Psychologist*, *19,* 111 - 130.

Nilsen, P - J. (2008). Golf putting: How shaft weight affects technique, performance and perception of shaft weight in competitive players. *Master thesis from Norwegian School of Sport Sciences*, Oslo, Norway.

Nilsson, J. & Karlsen, J. (2006). A new device for evaluating distance and directional performance of golf putters. Journal of Sports Sciences, 24, 2, 143 - 147.

Pelz, D. (1989). *Putt like the pros*. New York, Harper Perennial.

Pelz, D. (1990). The long putter. *The Pelz Report*, *1*, 3.

Pelz, D. (1994). A study of golfers´ ability to read greens. In, A. J. Cochran & M. Farrally (Eds.) *Science and Golf II: Proceedings from the World Scientific Congress of Golf,* 180 - 185. London, Routledge.

Pelz, D. (2000). *Dave Pelz´s putting bible*. New York, Doubleday.

Potts, A. D. & Roach, N. K. (2002). Putting alignment in golf: a laser-based evaluation. In E. Thain (Ed.), *Science and Golf IV: Proceedings of the World Scientific Congress of Golf*, 141 - 150. London, Routledge.

Sidowski, J. B., Carter, K. & O´Brian, T. (1973). Variables influencing “lining up the shot” in golf putting. *Perceptual and Motor Skills*, *26*, 39 - 44.

Smith, A. M., Adler, C. H., Crews, D. *et al.* (2003). The ‘yips’ in golf: A continuum between a focal dystonia and choking, *Sports Medicine*, *33*, 13 - 31.

Smith, A. M., Malo, S. A., & Laskowski, E. R. (2000). A multidisciplinary study of the 'yips' phenomenon in golf: An exploratory analysis. *Sports Medicine, 6,* 423 - 437.

Sörenstam, A. (2007). *Golf Annika’s way*. New York, Gotham Books.

Steinberg, G. M., Frehlich, S. G. & Tennant, L. K. (1995). Dextrality and eye position in putting performance. *Perceptual and Motor Skills, 88,* 424 - 426.

Sugiyama, Y., Nishizono, H., Takeshita, S. & Yamada, R. (2002). Eye dominance, visibility, and putting performance. In E. Thain (Ed.), *Science and Golf IV: Proceedings of the World Scientific Congress of Golf, 151 - 156.* London, Routledge.

Thomas, P. R., Neumann, D. L. & Hooper, S. L. (2008). Attentional focus and putting performance at different levels of skill development. *In, D. Crews & R. Lutz (Eds.), Science and Golf V: Proceedings of the World Scientific Congress of Golf,* 224 - 231. Mesa, AZ, Energy in Motion.

Tierney, D. E. & Coop, R. H. (1998). A bivariate probability model for putting proficiency. In, M. R. Farrally & A. J. Cochran (Eds.), *Science and Golf III: Prodeedings of the World Scientific Congress of Golf,* 385 - 394. Champaign, IL, Human Kinetics.

Werner, F. D. & Greig, C. (2000). *How golf clubs really work and how to optimize their designs*. Jackson, WY, Origin.

Woods, T. (2005). Stick to your routine. *Golf Digest, 56*, 8, 39.

Appendix I. *Calculation example of stroke direction variability and relative importance of face angle, putter path and impact point*

Calculation of stroke direction variability

The intended direction for each stroke was defined as the direction where the putter head (face angle) was aimed when addressing the ball before starting the back swing (actual aim line). Because of the players' inability to aim consistently, the actual aim line differed from stroke to stroke even though the target was the same. Variability in face angle and putter path was expressed as standard deviation (*s*) in degrees. Variability in horizontal impact point was expressed as standard deviation (*s*) in millimetres. Effective variability was calculated by multiplying variability by known coefficients of how much each parameter affects initial direction (effective variability = face angle variability · 0.83 (Pelz, 2000), putter path variability · 0.17 (Pelz, 2000) and impact point variability · 0.034 degrees·cm^{-1} (Nilsson & Karlsen, unpublished data)). Based on the effective variability of face angle, putter path and impact point and the covariance between each pair of parameters, stroke direction variability (which equals variability of the stroke deviation angle in Figure 17) for each player was calculated with the following equation.

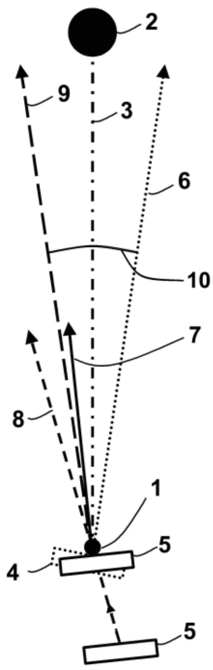

Figure 17. *Top-view schematic drawing describing different parameters relevant for aim and stroke: (1) the ball, (2) the hole, (3) ball-hole line, (4) putter head at address, (5) putter head in down swing and at impact, (6) actual aim line, (7) face angle direction at impact, (8) putter path direction, (9) initial ball direction, which is decided by face angle, putter path and impact point, (10) stroke deviation angle (Figure from Karlsen, Smith & Nilsson, 2008)*

Eq. 4. *Stroke direction variability*

$$= [\text{effective variance}_{\text{face angle}} + \text{effective variance}_{\text{impact point}} + \text{effective variance}_{\text{putter path}} + 2\cdot(\text{covariance[face angle, impact point]} + \text{covariance[face angle, putter path]} + \text{covariance[impact point, putter path]})]^{-2}$$

Calculation of the relative importance of face angle, putter path and impact point

How much a certain improvement in one of the three parameters (face angle, putter path and impact point) variability affected overall stroke direction consistency (relative to each other), was defined as each parameters' relative importance for stroke direction consistency. The relative importance was expressed in percent, with the total relative importance of the three parameters equal to 100 %.

Calculation example

Calculation methods are described closer with an example from one top international player. This player had a variability in face angle at impact (relative to where the face was aimed at address) of 0.39°. Variability in putter path was 0.65° and variability in horizontal impact point on the club face was 2.6 mm. Effective variability for this player was for face angle: 0.32° (0.39° · 0.83), putter path: 0.11° (0.65° · 0.17) and impact point: 0.09° (2.6 mm · 0.34° mm^{-1}). Stroke direction variability was then calculated according to Eq. 5:

Eq. 5. *Stroke direction variability* = $[(0.32°)^2 + (0.11°)^2 + (0.09°)^2)] + [2·(0.0060° + 0.0066° + (-0.0073°))]^{-1}$

Stroke direction variability = 0.368°

Importance of face angle, putter path and impact point for stroke direction variability is defined as how much a small improvement in one of the parameters affect overall stroke direction variability: A 10 % improvement in face angle variability from 0.65° to 0.58° results in an improvement in stroke direction variability of 0.0289° (0.368 to 0.329°) . A 10 % improvement in putter path variability from 0.39° to 0.35° results in an improvement in stroke direction variability of 0.0030° (0.368 to 0.365°). A 10 % improvement in impact point variability from 2.6 mm to 2.4 mm results in an improvement in stroke direction variability of 0.0017° (0.368 to 0.366°).

Relative importance of face angle for stroke direction consistency would then be $0.0289°·(0.0289 + 0.0030 + 0.0017)^{-1} = 86\ \%$

Relative importance of putter path for stroke direction consistency would then be $0.0030°·(0.0289 + 0.0030 + 0.0017)^{-1} = 9\ \%$

Relative importance of impact point for stroke direction consistency would then be $0.0017°·(0.0289 + 0.0030 + 0.0017)^{-1} = 5\ \%$

For these calculations we assume that the covariance between the three parameters stays constant when this player is improving. Corresponding mean values for all subjects are presented in Table 6.

Appendix II. *Calculation of the relative importance of green reading, technique and green inconsistencies for distance variability*

Throughout the putting process there is a propagation of errors which affects distance variability. The overall distance variability is a product of the variability in green reading, technique and green inconsistencies, and can be calculated with the following equation:

Eq. 6. *Distance variability =((green reading variability)^{2} + (technique variability)^{2} + (green inconsistency) ^{2})$^{-2}$*

The equation is derived from the equation for calculating the total standard deviation of several independent measurements where the standard deviation of each measurement step is known: $S_{total} = \sqrt{S_1^2 + S_2^2 + S_3^2} + ...S_k^2$ (DeMuth, 2006). The assumption that the variability of green reading, technique and green inconsistencies are independent is discussed below. The estimation of relative importance of green reading, technique and green inconsistency for distance variability were done through a 4-step process which includes estimating the distance variability caused by green inconsistencies, putting technique and green reading, in addition to comparing the relative importance of those three factors

<u>Step 1: Estimating distance variability caused by green inconsistency</u>

Green inconsistency was estimated by rolling out 20 balls in the middle of the test area (Top Flite Strata TL-Tour) with the same speed and from the same spot with a True Roller^{TM} (ball ramp). Relative variability in roll distance was 2.5 %. The True Roller was validated by ten times rolling a series of 10 balls while measuring the initial ball speed by help of two pair of photocells. The average relative initial ball speed variability in the validation test was 0.4 %.

<u>Step 2: Estimating distance variability caused by putting technique</u>

Putting technique variability was calculated with the following equation:

Eq. 7. *Technique variability = ((distance variability)^{2} – (green reading variability)^{2} –(green inconsistency) ^{2})$^{-2}$ = <u>6.3 %</u>*

We made the assumption that if a good player hit the same putt a number of times in a short period of time, that player would know very well what the correct initial velocity would be. It is reasonable to assume that the player would gain a very good green read of that specific putt after doing several trials. Distance deviation from the target line in the “30 putt test” seemed to be relatively equal in the last 15 trials

(Figure 18). In the “30 putt test” we therefore assumed that green reading variability was zero for the last 15 putts. The variability caused by green inconsistency (2.5 %) from “Step 1” was also used for calculations together with the average measured distance variability of 6.8 % in the last 15 trials of the repeated putt test.

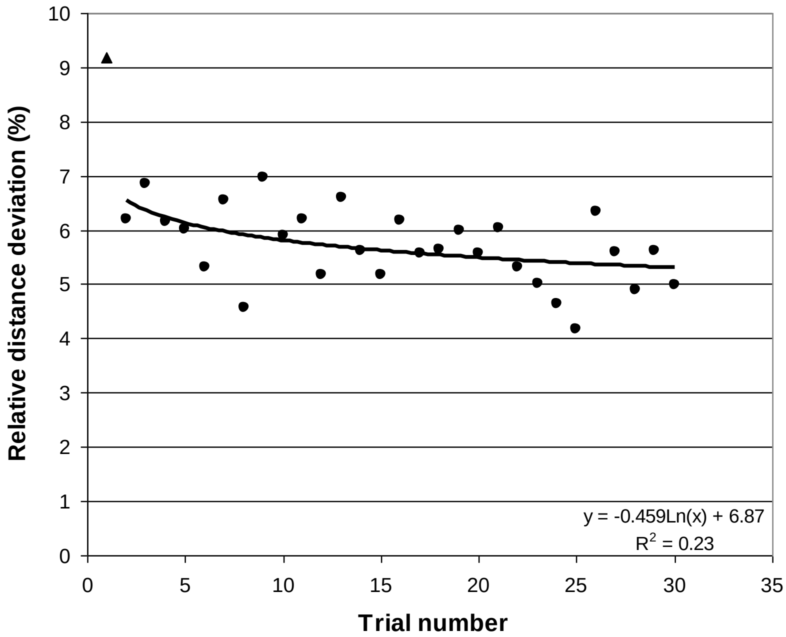

Figure 18. *Relative distance deviation over 30 repeated trials (●). There was a large reduction in distance deviation from the first (▲) to the second trial. As indicated by a logarithmic regression model there was a small reduction in distance deviation from trial two and on ($p < 0.01$). There were no significant changes in performance when analyzing the last 15 trials only with a linear regression model ($p = 0.12$), indicating that performance were relatively stable (Figure from Karlsen & Nilsson, 2008c).*

Relative distance variability caused by technique in the “30 putt test” was found to be 6.3 %.

Step 3: Estimating distance variability caused by green reading

Next step was to estimate green reading variability in a test similar to golf play, with the following equation:

Eq. 8. *Green reading variability = ((distance variability)^2 – (technique variability)^2 – (green inconsistency) ^{2})$^{-2}$ =* 8.2 %

The average distance variability of 10.6 % from the "40 putt test", together with the distance variability of 6.3 % caused by technique from step 2 and the distance variability of 2.5 % caused by green inconsistencies from step 1 were used for the calculation. The players average distance variability caused by green reading was found to be 8.2 % of the putt distance.

Step 4: Comparing the three different sources of distance variability

The relative importance of each parameter for distance variability was calculated by the following equations:

Eq. 9. *Relative importance of green reading = (green reading variability)^2/((green reading variability)^2 + (technique variability)^2 + (green surface variability^2)) = 60 %*

Eq. 10. *Relative importance of technique = (technique variability)^2/((green reading variability)^2 +(technique variability)^2 + (green surface variability)^2) = 34 %*

Eq. 11. *Relative importance of green inconsistency = (green surface variability)^2/((green reading variability)^2 +(technique variability)^2 + (green surface variability^2)) = 6 %*

Input to these equations were the measures of distance variability caused by green inconsistency (2.5 %, from step 1), technique (6.3 %, from step 2) and green reading (8.2 %, from step 3).

Assumptions which the calculations are based on

Variance analysis in the present study are based on the assumption that the distance variability caused by green reading, technique and green inconsistency are independent variables.

It seems clear that the undetected inconsistencies of the green are independent of the green reading and putting technique variability due to the fact that the inconsistencies affects the ball roll after the green is read and the ball is hit.

It also seems reasonable to assume that technique variability is independent of green reading variability. In this context the putting technique is defined to start in the moment the player starts to move the putter in the back swing, and it lasts until impact (approximately 1 s). It is reasonable to think that the players during this time did not have any new inputs that could affect their green read for distance throughout the second the technique lasts, especially since the players look at the ball and not at the area they will putt over during execution of the technique.

The improvement in distance control over trials in the "30 putt test" has been related to green reading only, and not to improvement in technique. This is based on analysis of the technique variability of 52 elite players (mean handicap = 0.5 ± 2.8, mostly from Paper I), who did between 20 and 30 repeated putts from about 4 m. There was no difference in technique variability in temporal parameters and impact point when comparing the first and second half of the putts in the series. This indicates that improvement over trials in the "30 putt test" was related to green reading and not technique.

Another assumption the present study is based on is that green reading for distance is perfect after doing 15 trials of the same putt. It is reasonable to think that an elite player is unable to completely understand the read for distance of one specific putt. If so, there would have been some green reading variability in the last 15 trials of the "30 putt test", and therefore the estimated distance variability caused by technique would have been lower, indicating that the importance of the green reading might be even higher than the reported 60 % in the present study.

Yet another assumption which the calculations are based on is that the 6 meter putt used for the repeated putt test represents the average of all putts in the 40 different putts test in terms of difficulty. This criteria seems to be met since there were no significant difference between the average relative distance deviation of the 40 different putts (8.5 %) and the first 6-meter putt from the "30 putt test" (9.2 %) ($p = 0.53$). Six meters also corresponded to the median length of the 40 different putts. In addition the average slopes at the target lines were the same at the two different tests ("40 putt test": 0.2 ± 1.2° uphill; "30 putt test": 0.1 ± 0.2° uphill)

Another question is how well the "40 putt test" represents difficulty of tournament play in terms of distance control. Since the "40 putt test" was done on one green, it probably made it easier for the players to read the green for speed compared to a tournament where they play on 18 different greens. So, the importance of green reading for distance variability in the present study might also for this reason be somewhat underestimated.

LIST OF PAPERS

I. Karlsen, J., Smith, G. & Nilsson, J. (2008). The stroke has only a minor influence on direction consistency in golf putting among elite players. *Journal of Sports Sciences*, 3, 243 - 250.

II. Karlsen, J. & Nilsson, J. (2008a). A new method to record aiming in golf putting - Applied to elite players", In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf V*, 395 - 401.

III. Karlsen, J. & Nilsson, J. (2008b). Golf players prefer mallet putters for aiming, but aim more consistently with blade putters, In, D. Crews & R. Lutz (Eds.), *Science and Golf V: Proceedings of the World Scientific Congress of Golf V,* 402 - 407.

IV. Karlsen, J. & Nilsson, J. (2007). Club shaft weight in putting accuracy and perception of swing parameters in golf putting. *Perceptual and Motor Skills,* 2007, 105, 29 - 38.

V. Karlsen, J. & Nilsson, J. (2008c). Distance variability in golf putting among highly skilled players: The role of green reading. In, S. Jenkins (Ed.), *Annual Review of Golf Coaching 2008*, 71 - 80.

Paper I

Denne artikkelen ble tatt ut av den elektroniske versjonen av doktoravhandlingen i Brage på grunn av copyright-restriksjoner.

This paper was removed from the electronic version of this PhD Thesis in Brage due to copyright restrictions.

CHAPTER 52

A New Method to Record Aiming in Golf Putting - Applied to Elite Players

Jon Karlsen, Norwegian School of Sport Sciences
Johnny Nilsson, Swedish School of Sport and Health Sciences & Norwegian School of Sport Sciences

ABSTRACT

The purpose of this study was to develop and evaluate a test for aiming in golf putting, and to apply this method to elite players. By using a 3D kinematical ultra-sound system in conjunction with a specially designed putting green with 16 different targets (distance: 0.4 - 4.5 m) spread out in an 120° angle from a start spot, we were able to do reliable and golf specific tests of aim variability. The method has been successfully applied to both research and coaching, and areas of use include: performance testing of elite players, testing for different aiming patterns, comparing the effectiveness of different aiming strategies, comparing different putter head designs and putter fitting. The elite group (n = 20, M handicap = +0.4, s = 2.6) aimed systematically left by 1.0°, which equals the edge of the hole from 3 meters. Mean individual aiming variability, expressed as standard deviation (s), was 0.92°, which means that the elite players were consistent enough to aim the putter face inside a hole on approximately 74 % of trials from 3 meters. Aiming is a greater source of direction error than the putting stroke which have been reported to have a variability of s = 0.54° for scratch players (Karlsen *et al*., 2008). This indicates that aiming ability is relatively important for holing short putts, and should be prioritized in the training of elite players.

Keywords: golf putting, aim consistency, aim direction, elite players, aiming strategies

INTRODUCTION

Holing short putts in golf is mostly dependent upon the ability to control the direction of the putt, which again is decided by green reading, aiming, the putting stroke and green inconsistencies. Deliberate training programs should be based on capacity analysis and the demands of performing the sport on the intended level. Capacity analysis requires reliable and valid tests in skills that affect performance. One such skill in golf putting is the ability to aim the putter face at a target.

Different methods for measuring aim direction have been used in research: fasten a putter to a rotatable mount (Neale and Andersson, 1966; Sidowski *et al*., 1973), lasers which are reflected by the putter face (Neale and Andersson, 1966; McGlynn *et al*., 1990), or inserted into the putter (Potts and Roach, 2001 and 2002) and three-dimensional kinematical systems (Karlsen, 2003; Marquardt, 2007). All researchers used the mean deviation from the target as the performance measure, but Karlsen (2003) and Marquardt (2007) also reported aim variability (of $s = 0.57°$ and $s = 0.67°$, respectively). Karlsen (2003) tested eight elite players (*M* handicap = +0.8) and Marquardt (2007) tested 99 ultra-elite tour professionals. The ability to aim consistently is probably much more important than the ability to aim at a target, which in our experience is relatively easy to adjust, while consistency seems to take longer time to develop.

One limitation in these earlier aim studies is that only 1-3 different targets were used. During a round of golf all putts are different and the ability to aim consistently at various targets with changes in light and shadows, grass cut lines and colour contours seems important for performance, and should therefore be reflected in a test. A limitation using lasers is that aligning the laser beam perpendicular out of the putter face is difficult. A laser also requires some kind of attachment to the putter head which could be visually disturbing.

An advantage with consistent aim is that the same stroke can be used on all putts. Karlsen *et al*. (2008) found that stroke direction variability was affected negatively if players had to correct the face angle from address to impact, therefore the optimal is both consistent and accurate aim. Measuring aim while putting golf balls could be inaccurate, and was therefore a limitation with the studies of Karlsen (2003) and Marquardt (2007). Often a player might correct a miss hit putt with a change in the aim, and aiming variability might increase because of a bad stroke. Therefore we consider measuring aim without hitting golf balls as a better strategy.

The purpose of the present paper was to present a new method for aim performance measurement done with a three-dimensional kinematical ultrasound system in conjunction with a specially designed putting green, and to record aiming from a group of elite players.

METHOD

Participants

The aiming green has been applied to different groups of players. In this paper data are presented from a group of 20 elite players with average handicap of +0.4, $s = 2.6$. Thirteen of the players were professionals, and there were 19 male and one female player.

Apparatus

The angle of the putter face in relation to the calibration line was recorded with a three-dimensional kinematical ultrasound system (SAM PuttLab, Science & Motion GmbH, Mainz, Germany, www.scienceandmotion.com). Attached to the shaft was a triplet with three 70 HZ ultrasound units which transmitted signals to a receiver unit (Figure 1). The SAM PuttLab is thoroughly described by Marquardt (2007).

A 6 x 4 meter carpet with rounded edges was used as aiming green. The green had one start spot and 16 different targets spread out in a 120° angle, and were placed on a flat horizontal indoor surface. There were eight target points marked as black crosses in a distance of 0.4 - 1.2 meters away from the start spot, and there were eight targets by means of white paint filled circle at the size of a standard golf hole (*d* = 108 mm) placed 2.5 - 4.5 meters away from the start spot. The targets were numbered from 1 - 16, alternating between short and longer targets, and randomly distributed throughout the 120° range. No targets were on the same line from the start spot, which was a small bump in the green assuring that a ball could be placed with high consistency in position. A calibration spot was marked approximately in the center of the 120°-range (Figure 1).

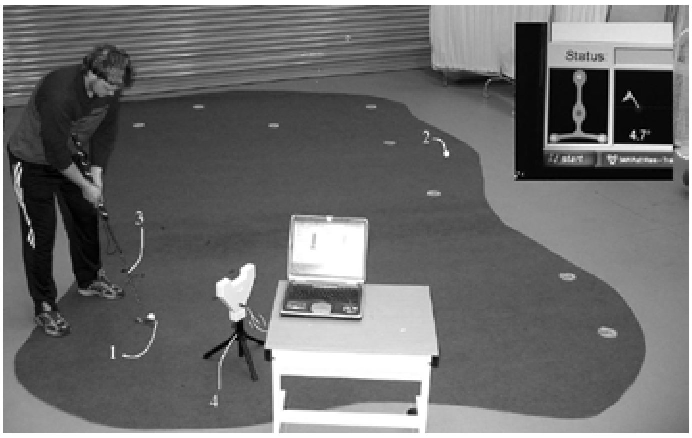

Figure 1 Aiming green. (1) start spot, (2) calibration spot, (3) triplet with three ultrasound transmitters, (4) receiver unit. The inset picture shows the SAM PuttLab where face angle can be read in real time with a resolution of 1/10th of a degree.

Calibration

The calibration procedure of the SAM PuttLab was somewhat modified from that described in the user manual. The test leader placed the putter face perpendicular to a thread which went from the calibration spot to the start spot. To reduce the possibility of introducing an offset angle during the tests the player also had to confirm that the putter was placed correctly before calibration. The thread was removed before testing.

Test procedure

One test consisted of 16, 32 or 48 aims (*M* = 27, *s* = 9) with the players own putter with the normal strategy for aiming (e.g. “line on ball”), in preferred tempo. The variations in number of trials were due to convenience and considered to have an insignificant influence on the results. When the player was satisfied with his aim a signal was given to the test leader which read the face angle in real time from the computer. No balls were hit, and no feedback was given during the test.

Methodological testing

Positioning of the targets

To find the angular position of each target a method using the SAM PuttLab and a geometrical method was used and compared.

The SAM PuttLab was calibrated with the calibration line at 0°. Then a putter was addressed with the aim line parallel to a thread which went through target number one and the start spot (Figure 2A). The face angle was read from the software and equaled the angular position of the target. This procedure was repeated eight times for each of the 16 targets, without recalibrating the system. The average of the eight measurements became the angular position of each target.

In the geometrical method, a thread which went through the start spot and the calibration spot was fastened to the green. By help of an angle, another thread which went through a target was fastened perpendicular to the first thread (Figure 2B). The distance from the start spot to the cross point between the threads and the distance between the target and the cross point between the two threads were measured, and trigonometric methods were then used to calculate the angular position of the target. The procedure was repeated twice for all targets, and the average values were used.

Variability of measurements

To attain reliable data we tested how well the putter was aimed, with use of a thread on eight series of 16 aims (one to each target) without recalibrating the system (Figure 2A). We also tested the variability of how well the test leader could replace two different putters perpendicular to the thread 10 times each, without assistance. The thread was not moved between the trials.

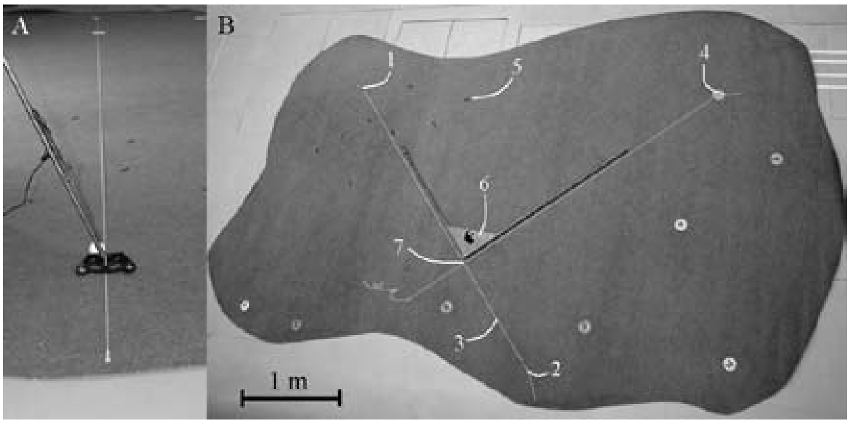

Figure 2 (A) Aiming green with a putter aligned to a thread which goes through the start spot and one of the targets. (B) Top view of the aiming green showing the geometrical method of determining the angular position of the targets, (1) start spot, (2) calibration spot, (3) calibration line, (4) one of the long targets, (5) one of the short targets, (6) angle, (7) cross point for threads.

RESULTS

Methodological testing

The mean difference between the 16 angular target positions using the "SAM-method" and the "geometrical method" was 0.28°, with the largest difference for a single target being 0.65°. The differences were mostly caused by what seemed like a small systematic linear underestimating of the angles by the 3D-system which equaled 0.4° at 60° away from the calibration line.

The average aim variability of the eight 16 aim-series was s = 0.19°. When the putter was addressed 10 repetitive times to a thread without assistance the test leader had a variability of s = 0.14 and 0.16° with a mallet and a blade putter respectively.

Elite player data

The elite players aimed the putter significantly left of the target ($p<.01$), with an average aim direction of 1.0° left, s = 1.4°. Average aiming direction was also 1.0° left when short and long aims were analyzed separately. Mean aiming variability was 0.92°, s = 0.25° on all aims, 0.78°, s = 0.31° on short aims, and 0.82°, s = 0.25° on long aims (Table 1). A linear regression analysis showed that players who aimed further away from the target had more variability in their aim ($p<.01$) (Figure 3).

Table 1 Aiming results for 20 elite players (mean handicap = +0.4)

	All aims	Short aims (0.4 - 1.2 m)	Long aims (2.5 - 4.5 m)
Aim direction ($M \pm s$)	1.0° left ± 1.4°	1.0° left ± 1.3°	1.0° left ± 1.6°
Range	4.0° left - 1.5° right	3.5° left - 1.3° right	4.5° left - 1.8° right
Aim variability ($M \pm s$)	0.92 ± 0.25°	0.78 ± 0.31°	0.82 ± 0.25°
Range (s)	0.50 - 1.37°	0.40 - 1.65°	0.49 - 1.28°

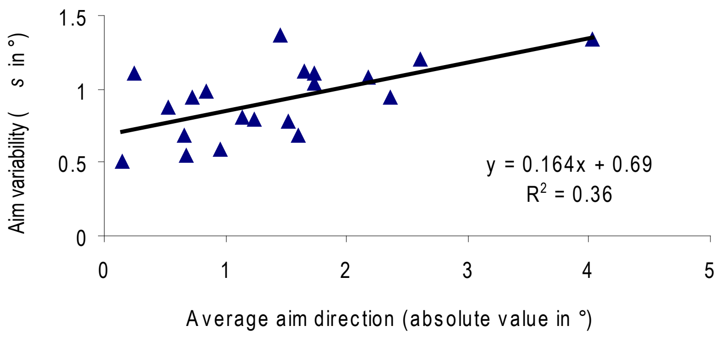

Figure 3 The relationship between how far away from the target the players aim on average and their aiming variability.

DISCUSSION

Methodological considerations

Because of a possible systematic underestimating of the angles by the SAM PuttLab, we decided to use the "SAM-method" for angular positioning of the targets. Since the underestimating seemed to be less than 1 % (0.4° per 60°) it would not affect the aim direction data. In addition we considered it beneficial to use the same system for both positioning of the targets and aim testing to assure reliable aim variability data .

The average aim variability of $s = 0.19°$ on the eight series included human variability in addressing the putter to the thread. The actual variability of the test method is therefore lower than 0.19° and far below the variability of the best elite players we tested, which had an aim variability of about 0.5° (Table 1). Therefore, we concluded that the aiming green used in conjunction with the 3D-system was a reliable method of determining aiming consistency for elite players.

Because the test leader was able to reproduce the calibration position of the putter relative to the thread with two different putter designs ($s = 0.14°$ and 0.16°, respectively) we assumed that aim direction could be measured with a reasonable accuracy. This is supported by the fact that disagreements between the test leader and the player about the calibration were rare. Anyhow, it is still a disadvantage that the calibration routine relies on the alignment skills of the test leader.

The method makes it possible to discover complex aiming patterns, and because different targets are used, it is more tournament specific than earlier methods. If a horizontal flat putting green is assured, the method can be used outdoors. Otherwise, if a slope is introduced, we have experienced that many players intuitively aim above the target. It is challenging to make flat outdoor greens with permanent high precision angular positioning of the targets, but this might be solved with an artificial outdoor green..

Elite player data

The elite players aimed systematically to the left by 1.0°, which corresponds to the change in face angle from address to impact of 0.6° opening by the elite players in the study of Karlsen *et al*. (2008). It seems that a common strategy by elite players is to aim slightly left and then open the putter face throughout the stroke. This is in contrast to the PGA-Tour players Marquardt (2007) tested, which on average aimed 0.35° to the right, with an average change in face angle from address to impact of 0.05° closing. The reason for this discrepancy is unknown at present. Karlsen *et al*. (2008) reported the average direction variability caused by the putting stroke itself to $s = 0.54°$ for scratch players. Compared to the aiming variability from the present study of $s = 0.92°$ this is relatively low. This indicates that aiming of the putter face is a more important factor for holing short putts than the putting stroke. Therefore coaching literature and elite players practice schedules on short putts should be more focused on aiming than on stroke technique. The further away the average aim direction was from the target, the higher the aim variability was. This indicates a benefit of avoiding compensations such as aiming left and opening the club face throughout the stroke to impact, or aiming right and closing the club face to impact. This corresponds with the finding of Karlsen *et al*. (2008) where stroke direction consistency increased with larger changes in face angle from address to impact.

APPLICATIONS

The method in the present study has several practical applications. It is a tool for the coach to analyze how players aim, and can also be used directly in training. In conjunction with technique analysis it is a powerful tool to analyse directional strategies. We have also used the aiming green to compare the effectiveness of different aiming strategies like "feeling aim", "intermediate target aim" and "line on ball aim" for single players. The aiming green has allowed us to discover and quantify different aiming patterns: "progressive aim", which means that aim direction varies systematically with distance; "fading aim", which means that aim is changing systematically in one direction throughout prolonged aim testing; "distance dependent variability", which normally means that some players aim more consistent on short than on long putts. The latter players might benefit from using an "intermediate target aim"-strategy. The aiming green can also be used by putter designers or in putter fitting, as it is possible to compare how well players aim with different putter head designs. In conclusion, using the aiming green in conjunction with a system accurately measuring face angle in real time is a very valuable tool both in research and coaching.

REFERENCES

Karlsen, J. (2003). Golf putting: an analysis of elite players technique and performance. Master thesis, *The Norwegian University of Sport and Physical Education,* Oslo, Norway.

Karlsen, J., Smith, G., & Nilsson, J**.** (2008). The stroke has only minor influence on direction consistency in golf putting among elite players. *Journal of Sports Sciences, 3*, 243-250.

Marquardt, C. (2007). "The SAM PuttLab: Concept and PGA Tour data", *Annual Review of Golf Coaching*, in press

McGlynn, F. G., Jones, R. & Kerwin, D.G. (1990). A laser based putting alignment test. In *Science and Golf I: proceedings of the First World Scientific congress of Golf* (pp. 70–75). E. & F.N. Spon.

Neale, D. C., & Anderson, B. D. (1966). Accuracy of aim with conventional and croquet-style golf putters, *The Research Quart., 37*, 87-94.

Potts, A. D., & Roach, N. K. (2001) A Laser-Based Evaluation of Two Different Alignment Strategies Used in Golf Putting. In P.R. Thomas (Ed.), *Optimizing Performance in Golf* (pp 104-111). Australian academic press Pty. Ltd.

Potts, A. D., & Roach, N. K. (2002). Putting alignment in golf: A laser based evaluation, In E. Thain (ed.), *Science and Golf IV: Proceedings of the World Scientific Congress of Golf* (pp. 142-150). Routledge.

Sidowski, J. B., Carter, K., & O'Brien (1973). Variables influencing "lining up the shot" in golf putting, *Perceptual and Motor Skills*, *26*, 39-44.

CHAPTER 53

Golf Players Prefer Mallet Putters for Aiming, But Aim More Consistently With Blade Putters

Jon Karlsen, Norwegian School of Sport Sciences
Johnny Nilsson, Swedish School of Sport and Health Sciences and Norwegian School of Sport Sciences

ABSTRACT

The purpose was to study aiming consistency in relation to putter head design, and how golf players perceived different putter head designs with respect to aiming. Over the last number of years there has been an increasing number of mallet type putter designs on the market, and putter club manufacturers often claim mallet putters are advantageous for aiming. Consistency in aiming was recorded from 32 club players (*M* handicap = 11.4, *s* = 10.8). Each player aimed with twelve different putters, six blade type putters and six mallet type putters, at 16 different targets placed 0.4 - 4.5 meters away from the start spot. The players aimed more consistently with the blade putters (*s* = 1.33°) than with the mallet putters (*s* = 1.41°) ($p<.05$). However, subjective ratings concerning the ability to aim with the different club heads were better for mallet putters compared to the blade putters ($p<.001$). Twenty-four of the thirty-two players rated the mallet putters as being easier to aim than the blade putters, with average ratings of 64.7 and 57.0, respectively, on a scale from 1 – 100. The discrepancy between subjective ratings and actual aim performance on putters indicate that it would be beneficial for players, putter fitters and putter designers to rely mostly on performance tests when designing and fitting golf putters with respect to aim performance. Although there were individual differences, the present study indicated that blade type putters were slightly better than mallet type putters for aiming.

Keywords: golf putting, aim consistency, putter head design, mallet putter, blade putter

INTRODUCTION

The competition between putter manufacturers is hard and numerous putter brands are available. Over the last years there has been a growth of specialized club makers, and a rising trend of individual putter club fitting. The Odyssey 2-Ball putter, which in December 2002 peaked with a US market share of 28.5 % (www.golfweek.com, 2007.11.26, Schupak, A.), has led the way for larger popularity of creative putter designs. Especially the number of mallet type putter designs has been increasing. Many putter manufacturers claim that the mallet type putters are easy to aim: "*These putters focus on revolutionary alignment and weighting technologies"* - about the Odyssey 2-Ball models (www.odysseygolf.com, 2008.01.10); *"The black anodized look is the perfect contrast to the five-sightline configuration making setup and alignment simple"* - about the Scotty Cameron Futura Phantom Mallet (www.scottycameron.com, 2008.01.10) and *"The Optigraphic Effect created by the body design and cavity insert improve your ability to align the putter with the target line"* - about the Ping Jas Craz-E One (www.pinggolf.com, 2008.01.10)

Research about the aiming characteristics of different putter designs is sparse. McGlynn *et al.* (1990) compared how well club players aimed with five different putters. They concluded that the subjects aimed a "rectangular shaped alignment putter" significantly better compared to the other putters. McGlynn *et al*. (1990) used the average deviation from the target as the performance measure. No published research is known to us on how golf players perceive different putter head designs for aiming purposes. Karlsen and Nilsson (2007) investigated putters with different shaft weight, and found that the perception of overall feeling of a particular putter club weight was not related to performance with that club. This may also be the case concerning perception of club design with respect to aiming and is therefore relevant to investigate.

The purposes of the present study was to compare how well club players aim with mallet type compared to more traditional blade type putters, and to investigate if mallet or blade putters are perceived to be easiest to aim with by the club players.

METHOD

Participants

Thirty-two golf players, thirty males and two females, participated in this study. Their mean handicap and playing experience were 11.4, s = 10.8 (range: +3.0 - 35.0) and 9.1, s = 5.3 years, respectively. Eighteen of the players normally played with a mallet type of putter, while the remaining fourteen played with a blade type putter.

Apparatus

The aiming of the participants was measured with a 3D kinematical ultrasound system (SAM-system, Science & Motion GmbH, Mainz, Germany, www.scienceandmotion.com) (Figure 1). The SAM-system consists of a triplet attached to the putter shaft which transmits ultrasound signals to a receiver unit, which again is connected to a computer with the SAM PuttWare 1.1 software. The SAM-system is made specifically for analysis of putter movement, but can also be used for real time face angle measurements. The aiming green had one start spot and 16 different targets which were divided into eight short targets (placed 0.4 - 1.2 meters from the start spot) and eight long targets (placed 2.5 - 4.5 meters from the start spot), spread out in a 120°-range from the start spot where a ball was positioned. The short targets were marked as small black crosses, and the long targets were marked as white painted circles at the size of a standard golf hole (d = 108 mm). The reliability of the SAM-system used in conjunction with the aiming green is sufficient for recording aim variability of elite golfers (Karlsen and Nilsson, 2008). Both the SAM-system and the method of using the SAM-system in conjunction with the aiming green are thoroughly described by Marquardt (2007) and Karlsen & Nilsson (2008) respectively.

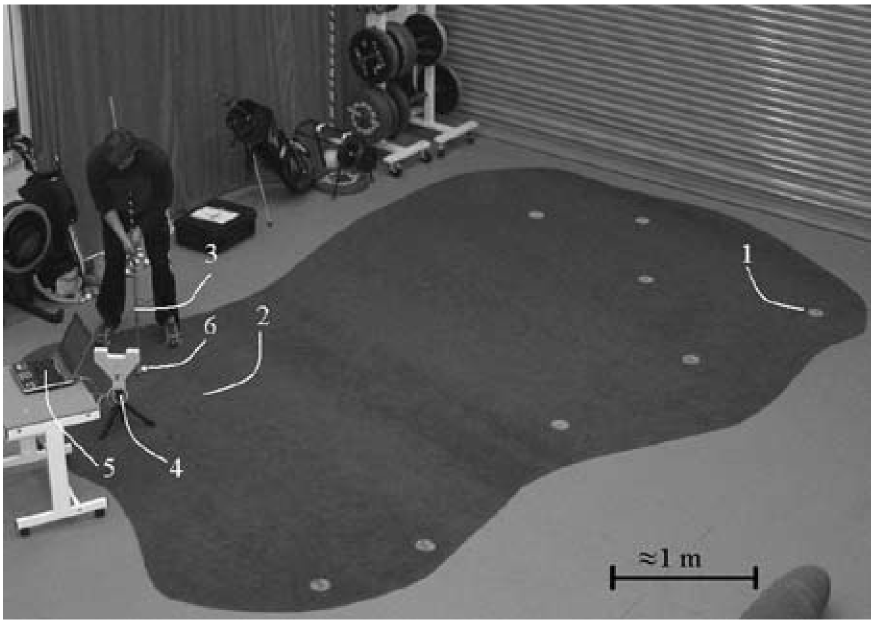

Figure 1 The test set-up with: (1) one of the long targets, 4.5 meters from the start spot, (2) short target area (3) triplet with ultrasound transmitters attached to the putter shaft, (4) receiver unit for ultrasound signals, (5) computer where real time face angle can be read in SAM PuttWare 1.1, (6) the start spot where a ball was placed.

Putters

Twelve different putters were divided into blade or mallet type putters (Figure 2)[1]. The main difference between the two types of putters is that the mallet putters have more mass extending rearward from the putter face than the blade putters. This allows the mallets to have aiming aids by means of lines, edges, circles, or similar with an extent decided by the mallet design (typically about 5

1 It should be noted that the authors have interest in a company manufacturing one of the mallet putters. Significance tests and conclusions will not be affected if that particular putter is taken out of the study.

- 9 cm). In comparison, the blade putters are without such aiming aids, or the aids are much shorter (typically less than 2 cm).

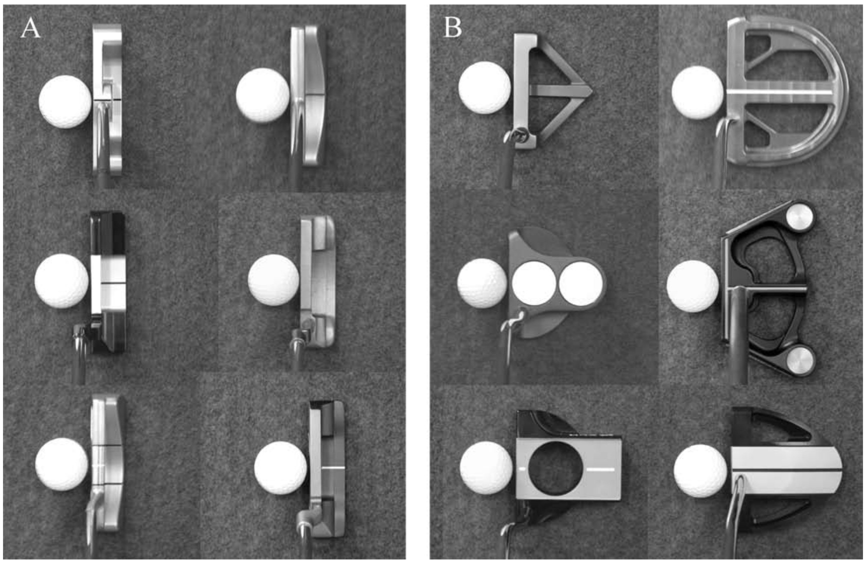

Figure 2 (A) The six blade type putters used in the present study, (B) The six mallet type putters.

100	-	Extremely easy
90	-	Very easy
80	-	
70	-	Easy
60	-	
50	-	Neither easy or difficult (average)
40	-	
30	-	Difficult
20	-	
10	-	Very difficult
0	-	Extremely difficult

Figure 3 Scale for subjective ratings of how easy the putters were to aim at the target.

Procedure

Each player did 16 aims with each putter, one aim to each target, without hitting the ball. The order of the putters was randomized, but the order of targets within each putter was always from 1 - 16. Thus a total of 6144 aims were recorded in the study. The players were not allowed to use a line on the ball to assist aiming. When the player was satisfied with his aim a signal was given to the test leader who read the face angle in real time from the SAM PuttWare 1.1 software. No balls were hit, and no feedback was given before all 12 putters were finished. After one putter was finished they answered the question: *"How easy, or difficult, do you think it was aiming with this putter?"* by giving a rating according to the scale in Figure 3. They rated the putter both for short and long targets, and they were allowed to use all integers from 0 - 100.

Conventional methods were used to calculate mean and standard deviation. A two-tailed t-test was used for significance testing of the difference between the putter types, and the measure of effect size was Cohen's *d* (Cohen, 1988).

RESULTS

All targets together the club players aimed blade putters (s = 1.33°) with less variability than mallet putters (s = 1.41°) ($p<.05$). The same tendency, but not statistically significant, was found when short and long targets were analyzed separately. There was no difference in average aim direction between the putter types, but there was a large difference in how the players rated the aiming with the putters ($p<.001$). Twenty-four of the thirty-two players rated the mallets easier to aim than the blade putters. For detailed results see Table 1.

Table 1 Aim variability, aim direction and subjective ratings for blade and mallet putters on all, short and long targets ($M \pm s$), along with effect size and p-value (two-tailed t-test) for a comparison between the two putter types.

	Blade putters	Mallet putters	Effect size	p-value
	Aim variability			
All targets (0.4 - 4.5 m)	1.33 ± 0.49°	1.41 ± 0.54°	0.14	0.02
Short targets (0.4 - 1.2 m)	1.02 ± 0.50°	1.10 ± 0.41°	0.17	0.06
Long targets (2.5 - 4.5 m)	1.35 ± 0.53°	1.41 ± 0.58°	0.12	0.12
	Average aim direction			
All targets (0.4 - 4.5 m)	0.8 left ± 1.8°	0.8 left ± 1.8°	0.01	0.82
Short targets (0.4 - 1.2 m)	0.9 left ± 1.6°	1.0 left ± 1.4°	0.03	0.65
Long targets (2.5 - 4.5 m)	0.7 left ± 2.2°	0.7 left ± 2.2°	0.00	1.00
	Subjective ratings			
All targets (0.4 - 4.5 m)	57.0 ± 9.0	64.7 ± 9.8	0.82	0.000
Short targets (0.4 - 1.2 m)	60.6 ± 10.3	68.3 ± 10.8	0.73	0.000
Long targets (2.5 - 4.5 m)	53.4 ± 9.6	61.1 ± 10.5	0.76	0.001

DISCUSSION

The major finding was a discrepancy between perception of aiming easiness and aim performance. Thus, even though the club players rated mallet putters easier to aim with, they actually aimed them with less consistency than the blade putters. It is likely that the strategy when aiming a blade putter is to visualize an imaginary line perpendicular to the putter face. This is also the most likely available strategy with irons and woods. A mallet type putter though invites an aiming strategy where the aiming aid (e.g. the aim line) can be visualized directly towards the target. This might intuitively look easy, but if we take all clubs in the bag into account golf players probably have much more experience seeing an aim line extending perpendicularly out of a club face. This could be an explanation of the discrepancy between perception of performance and performance. Thus, by using mallet type putters the players need to switch between two strategies instead of using one predominant aiming strategy for all clubs. Presumably, extensive training will reduce the variability that might be related to this switch in aiming strategy. Another possible explanation is that the marketing of the mallet putters aiming advantage have affected the participants.

Contradictory to McGlynn *et al*. (1990) we consider consistency as the primary performance measure for aiming. Our experience from coaching is that aim direction is relatively easy to improve while aiming consistency takes longer time to develop. This is supported by post-hoc linear regression analysis from the present study which showed that average aim deviation from the targets was not related to handicap ($p=0.64$), while aiming variability was related to handicap, with the low handicappers being more consistent ($p<.05$).

APPLICATIONS

The results can be applied by putter designers, putter fitters and serious players that would like to customize their putter to optimize their aiming strategy. Both a putter design process and a custom fitting process should rely more on aim testing than on subjective evaluation by players.

REFERENCES

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*, Hillsdale, NJ, Erlbaum..

Karlsen, J., & Nilsson, J. (2007). Club shaft weight in putting accuracy and perception of swing parameters in golf putting. *Perceptual Motor Skills*, *105*, 29-38.

Karlsen, J., & Nilsson, J. (2008). A new method to record aiming in golf putting - applied to elite players, In *Science and Golf V: proceedings from the World Scientific Congress of Golf V*, in press.

Marquardt, C. (2007). The SAM PuttLab: Concept and PGA Tour data. *Annual Review of Golf Coaching*, in press

McGlynn, F. G., Jones, R., & Kerwin, D.G. (1990). A laser based putting alignment test. In *Science and Golf I: proceedings of the First World Scientific congress of Golf* (pp. 70-75). E. & F.N. Spon.

Perceptual and Motor Skills, 2007, 105, 29-38.

CLUB SHAFT WEIGHT IN PUTTING ACCURACY AND PERCEPTION OF SWING PARAMETERS IN GOLF PUTTING [1]

JON KARLSEN AND JOHNNY NILSSON

Norwegian School of Sport Sciences

Norwegian School of Sport Sciences
The Swedish School of Sport and Health Sciences, Stockholm

Summary.—This study assessed how shaft weight influenced golf putting accuracy and subjective perception of swing parameters. Three putters of different shaft weight (100, 420, and 610 gm) were tested by 24 club players. Distance and deviation in direction were measured, and subjective ratings of the putters recorded. Subjects hit the ball further with lighter shafts. The mean distance hit was 100.2, 99.3, and 98.1% of the target distance for the normal, medium, and heavy putter shafts, respectively. Subjectively, the medium heavy putter was rated best on "overall feeling" and it was also rated better than the normal on"feeling of stability in the downswing." The heaviest putter was rated as too heavy by 23 of 24 subjects. There were no significant differences between the putter clubs in distance and directional putting accuracy. The major findings are that the golfers putted 2.1% longer with the 100 gm shaft than with the 610 gm shaft and that the perception of overall feeling of the putter club was not related to performance.

To master the game of golf, one must control several different types of shots. For the ten best players on the USPGA Tour and the PGA European Tour, 40.6% of the shots were putts in 2004;[2] therefore, putting can be said to be the single most important shot in golf with respect to occurrence. Superb putting depends upon several factors, such as tactics, green reading, aiming, and putting technique (Pelz, 2000). Although performance in putting depends mostly on the player, the equipment, including the putter, may help to optimize performance. The perceived importance of the putter club may be shown indirectly by the large number of putter designs on the market.

Some researchers have investigated how designs for different putters affect accuracy in putting. Pelz (1990) compared performance with long and conventional putters and concluded that the long putter was best on short putts (3 ft or 0.9 m), equally good on medium putts (9 ft or 2.7 m), and worst on long putts (20 ft or 6.1 m). Gwyn and Patch (1993) compared performance using long putters and putters of traditional length. They reported

---

[1]Address correspondence to Jon Karlsen, Norwegian School of Sport Sciences, P.O. Box 4014 Ullevål Stadion, NO-0806 Oslo, Norway or e-mail (jon.karlsen@nih.no). The authors thank Prof. Gerald Smith for scientific advice and writing assistance, and the staff and members at Hofors Golfklubb for making the data collection possible.

[2]www.pgatour.com and www.europeantour.com

DOI 10.2466/PMS.105.1.29-38

no significant difference in number of putts taken among 88 novice players when playing nine holes on a practice green. Gwyn, Ormond, and Patch (1996) compared performance using a traditional blade-putter and a cylindrically formed putter head and found no significant difference in putting accuracy. McGlynn, Jones, and Kerwin (1990) had a different approach to investigate the performance with different putters as they compared how designs of five club heads affected aiming for 30 players of varied skill, from scratch-players to beginners. What they called a "rectangular-shaped aim-putter" was significantly easier to align than four other designs.

The weight of the putter is a factor that may affect putting performance. Although it is not common, club heads of great variation in weight are available (approximately 250–700 gm, but most putter heads weigh around 350 gm). Traditional putter shafts weigh approximately 100 gm for those of usual length (34 in. or 860 mm), but putters with shaft weights up to 500 gm are in use by some professional players. It appears no research has been conducted on how the weight of the shaft affects perception of stability and putting performance. The mass of the shaft, in contrast to the mass of the club head, can be altered without strong influence on the club's effective mass at impact,[3] so the present study focused on how the shaft weight may influence perception of stability, weight feeling, and performance in putting.

Method

Subjects

A total of 24 club players participated. Their mean handicap was 19.4 ($SD = 13.6$; range 0.1 to 36), and age was 36.5 yr. ($SD = 14.9$). Five players did not have an official handicap so their handicaps were set to 36.0, which is the highest official handicap possible. Mean golf-playing experience was 8.4 yr., ($SD = 7.4$). All players were right-handed.

Experimental Design and Analysis

Three putter of different shaft weight (100, 420, and 610 gm) were used. All shafts were made of steel. The common putter had a traditional steel shaft (100 gm) with a slightly increasing diameter from tip to butt. The two heavier putters had parallel shafts. The grip was of the same type and weight (60 gm) on all putters. Putter head of all putters was a toe-heel weighted model from Brassmaster, with a quite long hosel (74 mm), weighing 310 gm.

Data collection was done over three days on a flat part of an outdoor

[3]Nilsson, J., & Karlsen, J. (2002) [How the shaft weight affect initial ball speed in golf putting]. Norwegian School of Sport Sciences, Oslo, Norway. Unpublished raw data.

practice green. The green was cut every day before testing, and stimpmeter values (device for assessing roll friction on golf greens), which were recorded several times each day, were between 7'6" and 8'4". Green conditions were dry and good all days, with outdoor temperature between 22 and 26°C and wind speed between 0 and 3 msec.^{-1}. After "warm-up" of 30 putts, 10 putts per club, each subject completed an additional number of 90 putts in the test. They had 10 putts on each at the three distances, 4, 8, and 12 m, using three different putters of a total club weight of 470, 790, and 980 gm, respectively. Before each new putt distance they had two "warm-up" putts. The subjects completed all 30 putts with one club, before changing to another club. The order of the clubs used was randomized. The order of distances (e.g., 4, 12, 8 m) for each club were also randomized, but each subject kept the same order of distances for all three clubs.

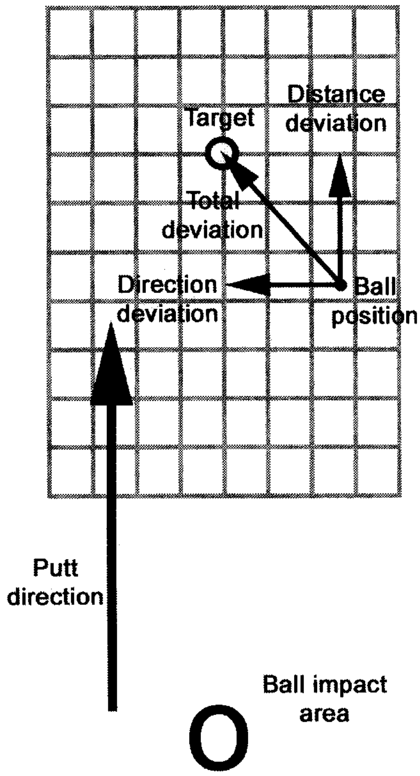

FIG. 1. Schematic drawing of the test setup design on the putting green, including different deviation parameters

The target was marked on the green as a circular surface at the size of a golf hole (diameter: 0.108 m). Around the target a grid consisting of 0.2 × 0.2 m squares was painted on the green by means of thin chalk lines. The grid was used to simplify the measurements of deviation in putt distance and direction. To minimize tracks from the balls on the green, the participants hit the ball anywhere from a circular shaped impact area of 0.3 m in diameter (Fig. 1).

The length of each putt for each of the club shaft weights was measured on all distances and it was expressed in percent of the target distance. Deviation in the putting direction for each club on each distance was expressed as the deviation from the target line in degrees. After each series of 10 putts all subjects rated the putter for "weight feeling," "feeling of stability in the downswing," and "overall feeling" on scales from 0 to 100 as described in Table 1.

TABLE 1

SCALES FOR RATING OF WEIGHT FEELING, FEELING OF STABILITY IN DOWNSWING, AND OVERALL FEELING

Weight Feeling	Feeling of Stability in Downswing	Overall Feeling
100 maximum heavy	100 maximum stability	100 extremely good feeling
90 too heavy	90 very stable	90 very good feeling
80	80	80
70 heavy (slightly too heavy)	70 stable	70 good feeling
60	60	60
50 neither light or heavy (perfect)	50 neither stable or instable	50 neither good or bad feeling
40	40	40
30 light (slightly too light)	30 instable	30 bad feeling
20	20	20
10 too light	10 very instable	10 very bad feeling
0 very light	0 no stability at all	0 extremely bad feeling

Statistics

Conventional statistical methods were used to calculate means and standard deviations. The mean values for each putter club were compared using methods for repeated measurement (Statistical Package for Social Sciences 11.0, SPSS Inc., USA). Maucley's test of sphericity initially tested the data. Greenhouse-Geisser correction was used if Maucley's test was significant. Given significant outcome on the global repeated measures test, individual t tests were used to assess differences in club conditions. A Bonferroni correction set the critical p values for significance at .02 (.05/3).

A Friedman test was applied to compare subjective ratings on the three clubs. When the global test was significant, a sign test was applied to examine which clubs were different. Critical p values for significance of the sign test were set at .02 (.05/3).

Results

Putting Distance and Direction

The mean putting distance for putters of different shaft weights showed in general that participants hit the ball further using lighter shafts. With the 100-gm shaft, the mean hitting distance was 100.2% of the aimed distance. This is significantly longer than the 98.1% of the aimed distance they hit the ball with a 610-gm shaft ($p < .001$). With the 420-gm shaft they hit the ball 99.3% of the aimed distance. Although it was a strong tendency, the 420-gm

TABLE 2
Mean Putted Length and Standard Deviations With Different Putters For 4-, 8-, and 12-m Target Distances and Mean Actual Putted Length on Three Distances: Percent of Aimed Distance

Shaft Weight (gm)	4 m		8 m		12 m		Overall (% of Aimed Distance)
	M	*SD*	*M*	*SD*	*M*	*SD*	
100	4.08	0.17	8.02	0.31	11.80	0.44	100.2
420	4.07	0.17	7.97	0.36	11.60	0.44	99.3
610	4.00	0.16	7.83	0.34	11.57	0.56	98.1

shaft was neither significantly different from the 100-gm shaft ($p = .08$) or the 610-gm shaft ($p = .02$) in putting distance (Table 2). There was no significant difference among the three putters for mean putting direction ($p = .30$) (Table 3).

TABLE 3
Mean Putting Direction and Standard Deviations With Different Putters For 4-, 8-, and 12-m Target Distances: Degrees

Shaft Weight (gm)	4 m		8 m		12 m		*M* All Distances	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
100	0.37 left	1.09	0.41 right	0.81	0.20 right	0.85	0.08 right	0.97
420	0.11 left	1.50	0.25 right	1.23	0.41 right	0.79	0.18 right	1.21
610	0.04 right	1.57	0.53 right	1.27	0.38 right	0.86	0.32 right	1.27

Putting Accuracy and Variability

No significant difference in accuracy among putters (100-, 420-, and 610-gm shafts) was found when the mean deviation from the hole was analyzed across all distances ($p = .45$) (Table 4). In addition, there were no significant differences when distance and direction deviations were analyzed separately ($p = .57$ and $p = .28$, respectively). Furthermore, there were no sig-

TABLE 4

MEANS AND STANDARD DEVIATIONS FOR TOTAL, DISTANCE, AND DIRECTION DEVIATION: PERCENT DEVIATION FROM TARGET FOR THREE PUTTERS WITH DIFFERENT SHAFT WEIGHT

M All Distances	Total Deviation From Hole		Distance Deviation		Direction Deviation	
	M	*SD*	*M*	*SD*	*M*	*SD*
100 gm	9.2	2.5	8.2	2.4	3.0	0.6
4 m	9.5	2.6	8.3	2.5	3.3	1.0
8 m	8.9	4.0	7.7	3.7	3.4	1.2
12 m	9.3	3.0	8.6	3.0	2.2	0.9
420 gm	9.2	2.9	8.0	3.0	3.2	0.9
4 m	9.2	3.3	7.8	3.2	3.7	1.2
8 m	8.8	3.6	7.5	3.7	3.5	1.0
12 m	9.5	4.1	8.8	4.1	2.4	1.0
610 gm	9.5	3.3	8.4	2.9	3.2	1.1
4 m	9.2	4.2	7.9	3.9	3.5	1.4
8 m	9.9	3.6	8.4	3.2	3.9	1.5
12 m	9.5	3.3	8.8	3.2	2.2	1.0

nificant differences between the putters when mean deviation from putting mean ($p = .73$), distance variability ($p = .75$), and direction variability ($p = .94$) were used as a measure of performance (Table 5).

TABLE 5

MEANS AND STANDARD DEVIATIONS FOR TOTAL DEVIATION, DISTANCE, AND DIRECTION VARIABILITY BASED ON MEAN ACTUAL PUTTED DISTANCE: PERCENT

M All Distances	Total Deviation From Putting *M*		Distance Variability		Direction Variability	
	M	*SD*	*M*	*SD*	*M*	*SD*
100 gm	8.4	2.5	9.7	3.1	3.4	0.8
4 m	8.2	2.7	9.3	3.6	3.7	1.5
8 m	8.2	3.6	9.3	4.6	3.9	1.4
12 m	8.6	3.0	10.4	3.8	2.6	1.1
420 gm	8.2	2.7	9.5	3.5	3.4	1.0
4 m	8.0	3.2	9.0	4.2	3.7	1.1
8 m	8.0	3.8	9.2	5.5	3.8	1.1
12 m	8.7	3.7	10.3	4.7	2.7	1.2
610 gm	8.5	2.8	9.7	3.7	3.4	1.1
4 m	8.2	3.9	9.3	4.9	3.6	1.3
8 m	8.9	3.7	10.0	4.8	4.1	1.7
12 m	8.3	2.5	9.9	3.5	2.6	1.2

A comparison of the total deviation and handicap showed participant performed significantly better when the handicap was lower ($p < .001$). The mean slope of the linear regression lines for all putters was .16 (Fig. 2), i.e., the participants' mean putting deviation was 0.16% better for each handicap point improved. There was no significant difference among the slopes of regression lines for the three putters.

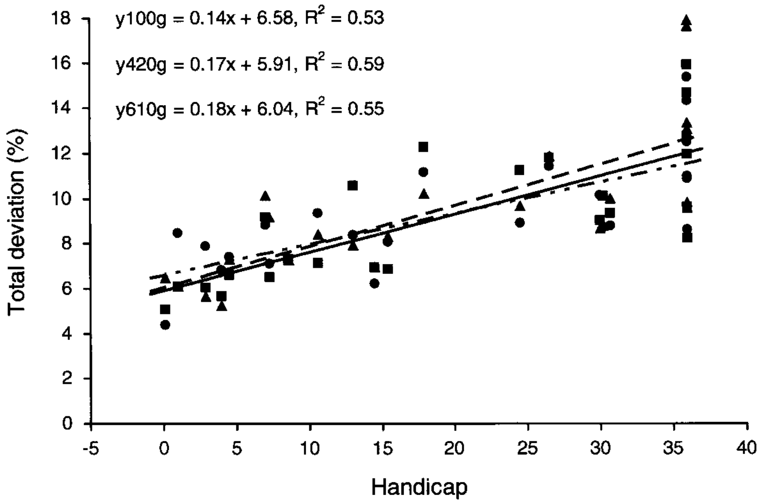

FIG. 2. Deviation from the hole versus players' handicap for putters of different shaft weight (● = 100 gm, ■ = 420 gm, ▲ = 610 gm)

Subjective Ratings of Putters

The ratings for "feeling of stability in the downswing," showed that the two heaviest putters were rated significantly better than the normal putter ($p < .01$). The conventional putter was rated 55.9 ($SD = 14.0$), the medium putter (420 gm) 71.7 ($SD = 16.8$), and the heaviest putter was rated 71.2 ($SD = 14.9$). All putters were rated differently on "weight feeling" ($p < .001$). The medium putter (420-gm shaft), and the conventional putter (100-gm shaft) were closest to 50 ("neither light, nor heavy"), with mean rating of 59.1 ($SD = 17.0$) and 39.6 ($SD = 9.1$), respectively. The heavy putter was rated at 74.2 ($SD = 11.9$) on "weight feeling." The medium putter had the highest score on "overall feeling" ($M = 69.1$, $SD = 18.0$, $p < .05$), but there was no significant difference between the conventional putter ($M = 58.7$, $SD = 16.5$) and the heavy putter ($M = 58.3$, $SD = 15.8$).

DISCUSSION

Analyses showed that the players hit the ball significantly shorter if shafts were heavier, even though they were aiming at the same target and had feedback from each shot, which made it possible to correct the distance during the series of 10 putts. The weight of the shaft had little influence on the initial ball speed for a given club head speed,[3] so shorter putting with heavier shafts may reflect greater force applied to the heavier putter to reach the same club head speed and the same putting distance as with a light putter. Getting accustomed to applying a greater force for a given distance probably takes some time, especially if a player is unaware that he needs the same club head speed with a heavy shaft to hit the ball the same distance.

Leading putter brands often print fitting options such as length, lie, grip size, head weight, and aiming characteristics on the putter. Since putts with different shaft weights give different putting lengths, the shaft weight may also be a parameter to consider in putter fitting. In unpublished data,[4] Karlsen, Smith, and Nilsson observed that elite players tend to putt the ball further on faster greens (relative to the target), so for a distance-accuracy point of view, players who consistently hit putts too far or play on fast greens may take advantage of a heavier shaft. Players who have a tendency to putt too short may prefer a lighter shaft.

In general, the players rated the medium weight putter (420-gm shaft) as best. It had a significantly better rating than the other two putters on "overall feeling," a better rating than the conventional putter on "feeling of stability in the downswing," and a better rating than the heaviest putter on "weight feeling." Although the players rated the medium weight putter as best, this was not supported by performance. There were no significant differences among putters, either in total deviation or distance and direction deviation from the hole. In addition, there were also no significant differences among putters in distance and direction variability. Bearing in mind that none of the players ever had tried a putter with a heavy shaft before the day of testing and that their mean playing experience with a conventional putter was 8.4 yr., the result for the medium weight putter may show over a longer time perspective that heavier shafts than today's conventional ones may be advantageous.

A few factors may have a positive effect when using a heavier shaft than normal, and these may explain the higher subjective rating of the medium putter versus the normal weight putter in "overall feeling" and "feeling of stability in downswing." A heavier putter shaft will increase the moment of inertia of the rotating system of upper body, arms, and club, which means that the rotational impulse from the muscles needed to reach a certain club head speed will be higher. Since the distance deviation was 2.6 times as large as the direction deviation (Table 2), controlling the rotational impulse and thus the club head speed will probably be the most important factor in putting technique. Generating a larger rotational impulse needed to reach a certain club head speed may be beneficial because the roll distance will not be so sensitive for a given absolute error in the impulse produced by the player. The question is how much the neuromotor system's accuracy of force/impulse production is affected if it has to create a larger impulse. According to

[4]Karlsen, J., Smith, G., & Nilsson, J. (2006) [Distance control in golf putting]. Norwegian School of Sport Sciences, Oslo, Norway. Unpublished raw data.

Carlton and Newell (1993), coefficient of variability (CV) in force production as a function of peak force (PF) and time to peak force (T_{pf}) is given by the following equation: $CV = \frac{1}{\sqrt{PF} \cdot \sqrt[4]{T_{pf}}}$. This function is based upon empirical data from several studies and is (Carlton & Newell, 1993) also relevant for impulse variability and thus for golf putting. The function of Carlton and Newell shows a decreasing CV when peak force is increased and time constant (T_{pf}) is not changed. That may be an argument for using a heavy shaft. Recent preliminary tests[5] show an increase in downswing time up to 20% when a heavy shaft is used instead of a normal shaft. This taken into consideration, the function of Carlton and Newell (1993) suggests that a heavy shaft may be even more helpful, since a longer movement time gives less variability.

Another critical question is how the directional accuracy of the movement of the club head is affected by increased muscle-force demands. Directional variability for tasks involving projectiles has not been studied extensively before (Carlton, Chow, & Shim, 2006). In earlier unpublished research[3] it was shown that the accuracy in the neuromotor control of face angle and impact point is unrelated to putting distance among elite players.[3] In that study, the players hit putts from 2 to 25 m, and the variability of the three deciding factors for initial ball direction (face angle, impact point and putter path) were measured. Variability in the putters' path was significantly greater at 2 m ($SD = 1.1°$) than at 8 m ($SD = 0.7°$) and 25 m ($SD = 0.7°$), indicating that the path of the club head was more stable as the swing speed increased. This can be understood mechanically as an error velocity component perpendicular to the intended direction introducing an angular deviation of club head path which is inversely related to club head velocity. The magnitude of angular deviation may in addition be related to club mass as any erroneous force would change velocity inversely with respect to the mass upon which it was applied, suggesting some benefit to a heavier shaft putter.

Another possible explanation of the good subjective ratings of the heavier shaft is increased stability. A heavier shaft would have a larger moment of inertia, resulting in a possible increase in the stability of the swing. This was also directly supported by the subjective ratings of the players. Only three of the 24 participants rated the conventional putter (100-gm shaft) as the most stable putter in the downswing. Influence by wind and involuntary forearm muscle contractions would probably not be as noticeable on the movement of the club head with a heavy shaft and may result in a smaller variability in putter path, impact point, and face angle.

However, results of the earlier unpublished studies[3,4,5] suggest that high-

[5]Karlsen, J., & Nilsson, J. (2006) [The effect of club shaft weight on putting technique]. Norwegian School of Sports Sciences, Oslo, Norway. Unpublished raw data.

er stroke intensity actually could be slightly beneficial for movement accuracy and so contradict Fitts' law for speed-accuracy tradeoff (Fitts, 1954), which states that accuracy of movements decreases with increases in movement speed. The reason these previous results differ from Fitts' law probably reflects that putts in golf are done at low movement speeds. Even a 25-m putt, which is very long, is perhaps only at about 20% of a players' capacity to produce club head speed. So a possible decrease in movement accuracy would probably occur outside the distance range of putts in golf.

Such results apply to how heavy the shaft should be. The heaviest putter (610-gm shaft) had a mean rating of 74.2 on "weight feeling" which was a bit heavier than the rating of "heavy" (70 on the rating scale). Only one of the 24 players rated it as the perfect weight; all the others rated it as more or less too heavy. This indicates that there is a limit on how heavy the shaft could be before it feels awkward for a person of a given muscle strength, and that the 610-gm shaft probably is near or over that limit for many players. This may be explained by the large momentum created by the heavy shaft, which again makes a large rotational moment at the wrists, especially in the downswing where acceleration is at the highest (Karlsen, 2003).

If the goal was to find a shaft weight that suits as many players as possible, subjective ratings indicate that this should be somewhere between the conventional and the medium shaft, maybe around 250 to 300 gm. One should be aware that shaft weight has to be considered together with club head weight. With higher or lower club head weights than normal, other shaft weights may be preferred. Also, variations in individual preferences known from this study are quite large.

REFERENCES

Carlton, L. G., Chow, J. W., & Shim, J. (2006) Variability in motor output and Olympic performers. In K. Davids, S. Bennett, & K. Newell (Eds.), *Movement system variability*. Champaign, IL: Human Kinetics. Pp. 85-108.

Carlton, L. G., & Newell, K. M. (1993) Force variability and characteristics of force production. In K. M. Newell & D. M. Corcos (Eds.), *Variability and motor control*. Champaign, IL: Human Kinetics. Pp. 15-36.

Fitts, P. M. (1954) The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.

Gwyn, R. G., Ormond, F., & Patch, C. E. (1996) Comparing putters with a conventional blade and cylindrically shaped club head. *Perceptual and Motor Skills*, 82, 31-34.

Gwyn, R. G., & Patch, C. E. (1993) Comparing two putting styles for putting accuracy. *Perceptual and Motor Skills*, 76, 387-390.

Karlsen, J. (2003) [Golf putting: an analysis of elite-players technique and performance]. Master's thesis from The Norwegian University of Sport and Physical Education, Oslo, Norway.

McGlynn, F. G., Jones, R., & Kerwin, D. G. (1990) A laser based putting alignment test. In A. J. Cochran (Ed.), *Science and golf I: Proceedings of the First World Scientific Congress of Golf*. London: E& F.N. Spon. Pp. 70-75.

Pelz, D. (1990) The long putter. *The Pelz Report*, 1, 3.

Pelz, D. (2000) *Dave Pelz's Putting bible*. New York: Doubleday.

Accepted May 25, 2007.

Distance Variability in Golf Putting Among Highly Skilled Players: The Role of Green Reading

Jon Karlsen[1] and Johnny Nilsson[1,2]
[1]Norwegian School of Sport Sciences,
PO Box 4014, Ullevål Studion, 0806 Oslo, Norway
E-mail: jon@putting.no
[2]The Swedish School of Sport and Health Sciences,
Stockholm, Sweden

ABSTRACT

The purpose was to quantify how important green reading, technique and green surface inconsistencies were for distance variability in putting among highly skilled players. Forty-three players (mean handicap = 2.8, s = 2.2) participated in the study. Their average relative distance variability (expressed as standard deviation) was s = 10.6% on a test including 40 different putts from 2.2 to 19.3 m, and s = 6.8% on the last 15 putts in a test with 30 repeated 6 m putts in the same direction. Relative distance variability caused by green surface inconsistency was s = 2.5%. A variance analysis of the putt data, based on assumptitions which lead to a conservative estimate of the importance of green reading, revealed that the relative importance of the determining factors for distance variability was: green reading (60%); technique (34%); and green inconsistency (6%). In conclusion, it seems beneficial for highly skilled players to put higher emphasis on green reading in distance control practice, and that coaches and researchers should focus more on developing methods and training programs for improving the green reading skill.

Key words: Distance Variability, Golf Putting, Green Reading, Putting Technique

INTRODUCTION

Superb golf performance depends on different skills involving driving, wood play,

Reviewers: Nic James (University of Wales Institute Cardiff, UK)
Phil Kenyon (Harold Swash Putting Ltd., UK)
Bryan McCullick (University of Georgia, USA)

iron play, short game and putting. Players on the different professional tours have a tight playing schedule with many tournaments and much travelling, so knowledge of how the different skills contribute to performance is therefore essential to make the right priorities in training. However, putting is the most important determinant of earnings on the USPGA Tour [1]. To perform well in putting, a player needs both distance and line control. According to Tierney and Coop [2], distance control explained most of the deviation from the hole in the PGA Tour veterans they analysed. The PGA Tour veterans had an average distance deviation of 6.5% of the putting distance, compared to a directional deviation of 1.3% of the putting distance.

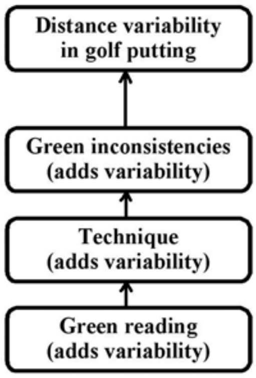

Figure 1. Factors Determining Distance Variability in Putting

FACTORS AFFECTING DISTANCE VARIABILITY IN PUTTING

In the present study, a three-factor model of distance variability in putting was used: green reading; putting technique; and green inconsistencies (Figure 1). Let us examine each factor.

First, a player has to evaluate the putt with the purpose of finding the correct initial ball velocity. The distance of the putt, the slope (uphill / downhill) and the green speed are the most important factors to evaluate with respect to initial ball velocity. Other factors might be wind, grain, dew and footprints. Green speed can be different from green to green, and even on the same green. All these evaluations are sources for variability in putting distance. Because these evaluations mainly are of green conditions, we define this process as green reading.

Second, the player has to perform his putting technique according to the green read. The purpose of the technique in distance terms is to start the ball with the initial velocity decided to be correct during the green read. Initial velocity is determined by the club head speed at impact, and the point of impact on the club face, where club head speed is the most important. Delay et al. [3] reported relative club head speed variability at impact on repeated 1 to 4 m putts as $s = 3.2\%$ for ten elite players, also Karlsen et al. [4] reported that 32 elite players had a relative club head speed variability of $s = 4.8\%$ on repeated 4-m putts.

A third factor affecting distance variability is the inconsistency of the green surface. According to Pelz [5], a player leaves more than 100 footprints on each green and many of them around the hole. In addition to inconsistencies from footprints, there are inconsistencies caused by sand, grass, mud and other very small imperfections in the surface. This makes it practically impossible to make a perfect prediction of the ball roll distance. In addition, ball roll distance will not be constant even if we roll balls on the green from the same spot, with the same speed. Koslow and Wenos [6] found distance variability due to inconsistencies in the green to be about s = 0.9% of the distance when they rolled balls from a secured ball ramp from 6 m on an outdoor green.

Given that green reading, putting technique and green inconsistencies affect the most important part of the game, it stands to reason that they be studied for their contribution to distance variability. To the best of our knowledge, no research has been devoted to this before. Therefore, our purpose was to quantitatively estimate the relative importance of green reading, putting technique and green inconsistencies for distance variability in a group of highly skilled players on a green similar in quality to what we find in elite tournaments.

METHODS

PARTICIPANTS

Forty-three highly skilled golf players volunteered for this study. Their mean handicap and age were 2.8, s = 2.2 strokes and 20.2, s = 6.7 years, respectively. Eight of the players were professionals, and three of the players had represented their national team. There were thirty-four male and nine female players, and all players had a handicap of 5 or less.

TEST CONDITIONS

Testing was conducted during two days on an approximately 600 m^2 outdoor two-tiered practice green (Figure 2). On the two different tiers, the green had some

Figure 2. Picture of the Putting Green

Approximately two thirds of the green used in the present study is shown. The numbers (1, 4, 5, 6 and 7) indicate the target lines for five of the seven fields in the “40 putt test”. The letters (a – f) indicate the start point for the six putts in field no. 1 (a = putt no. 1, 3.30 m; b = putt no. 8, 14.10 m; c = putt no. 15, 9.60 m; d = putt no. 22, 12.30 m; e = putt no. 29, 16.40 m and f = putt no. 36, 2.60 m). The arrow shows the general direction of the putts in field no. 1. The inset picture show how the start spot for each putt was marked.

undulations, but some parts were also relatively flat. Stimpmeter values were recorded nine times in total over two days and were on average 9’8” (range: 9’1” to 10’4”), which corresponds with the average reported Stimpmeter values of 10’3” from PGA European Tour tournaments in 2006. The green was moved before testing both days.

TEST PROCEDURE

After a five-minute free warm-up session, each participant performed a total of 70 putts on two different tests. First, they played a 40-putt course (“40-putt test”) with both flat, downhill, uphill, moderate left-to-right break, moderate right-to-left break, up-tier and down-tier putts ranging from 2.2 to 19.3 m (median distance was 6.0 m). The players were instructed to stop the ball as close as possible to a target line on the green, and they were told that it was equally good to stop for example 30 cm short of the line as 30 cm past the line. Each player was equipped with a metre ruler and a scorecard, and they measured the distance deviation (perpendicular to the target line) of their own putts. Test leaders double-checked some of the measurements, and did not find any measuring errors. Because of space limitations, the 40 different putts were arranged in seven different fields of 5 to 6 putts which had the same target line. The course was set up so the players always switched to a different field between each putt.

After doing the “40-putt test”, all players did 30 repetitive putts from the same starting spot to a target line 6 m away (“30-putt test”). Also in this test, they were instructed to stop the ball as close as possible to a target line. They hit all putts in their own chosen inter-stroke tempo, and deviation in distance was measured by another player. To limit green inconsistencies caused by the players, three different parallel fields were used.

Green slopes were measured with a digital water level (Breakmaster, www.exelys.com). The slope at the target lines in the seven different fields of the “40 putt test” were 0.2°, s = 1.2° uphill, which corresponded to the average slope of the three different fields used for the repeated putts test of 0.1°, s = 0.2° uphill.

CALCULATION OF RELATIVE DISTANCE DEVIATION

In the “40-putt test”, the relative deviation was measured for each putt. If, for example, a player putted 60 cm short on a 6-m putt, the relative distance deviation on that putt was 10%. A player’s relative distance deviation on the test was calculated as the average relative distance deviation from the 40 different putts. The same procedure was used for the “30-putt test.”

STATISTICAL CALCULATIONS

Relative Importance of Green Reading, Technique and Green Inconsistency for Distance Control

Throughout the putting process, there is a propagation of errors which affects distance variability. The overall distance variability is a product of the variability in green reading, technique and green inconsistencies, and can be calculated with the following equation:

Distance variability = ((green reading variability)^2 + (technique variability)^2 + (green inconsistency) ^{2})$^{-2}$

The equation is derived from the equation for calculating the total standard deviation of several independent measurements, where the standard deviation of each measurement step is known: $S_{total} = \sqrt{S_1^2 + S_2^2 + S_3^2 + \dots S_k^2}$ [7]. The assumption that the variability of green reading, technique and green inconsistencies are independent is discussed later in the paper. A similar methodology has earlier been used for the directional aspects of the putting stroke [8]. The estimation of the relative importance of green reading, technique and green inconsistency for distance variability are done through a 4-step process.

Step 1: Estimating Distance Variability Caused by Green Inconsistency

Green inconsistency was estimated by rolling out 20 balls in the middle of the test area (Top Flite Strata TL-Tour) with the same speed and from the same spot with a True Roller^{TM} (ball ramp). Relative variability in roll distance was $s = 2.5\%$. The True Roller was validated by rolling a series of 10 balls ten times, while measuring the initial ball speed using two pairs of photocells. The average relative initial ball speed variability was $s = 0.4\%$.

Step 2: Estimating Distance Variability Caused by Putting Technique

Putting technique variability was calculated with the following equation:

Technique variability = ((distance variability)^2 – (green reading variability)^2 – (green inconsistency) ^{2})$^{-2}$

We made the assumption that if a good player hit the same putt a number of times in a short period of time, that player would know very well what the correct initial velocity would be. It is reasonable to assume that the player would gain a very good green read of that specific putt after doing several trials. Distance deviation from the target line in the "30-putt test" seemed to be relatively equal in the last 15 trials (Figure 3). In the "30-putt test", for the calculations, we therefore assumed that green reading variability was zero for the last 15 putts. The variability caused by green inconsistency ($s = 2.5\%$) from "Step 1" was also used for calculations together with the average measured distance variability of $s = 6.8$ % in the last 15 trials of the repeated putt test. Relative distance variability caused by technique in the "30-putt test" was found to be $s = 6.3\%$.

There was a large reduction in distance deviation from the first (▲) to the second trial. As indicated by a logarithmic regression model, there was a small reduction in distance deviation on trial two and subsequent trials ($p < 0.01$). There were no significant changes in performance when analyzing the last 15 trials only with a linear regression model ($p = 0.12$), indicating that performance was relatively stable.

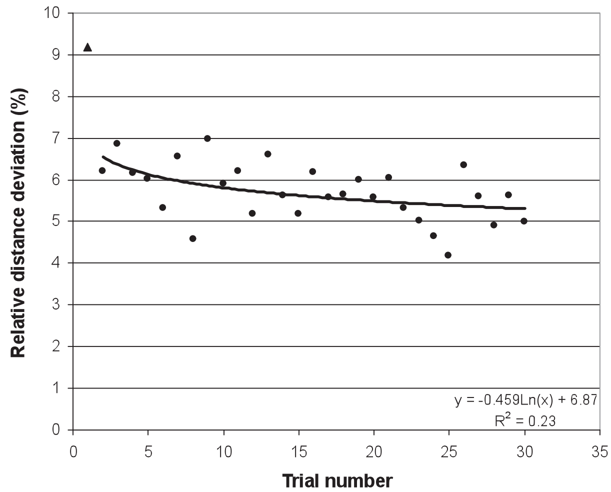

Figure 3. Relative Distance Deviation Over 30 Repeated Trials

Step 3: Estimating Distance Variability Caused by Green Reading
The next step was to estimate green reading variability in a test similar to golf play, with the following equation:

> Green reading variability = ((distance variability)^2 – (technique variability)^2 – (green inconsistency) ^{2})$^{-2}$

The average distance variability of s = 10.6% from the "40-putt test", together with the distance variability of s = 6.3% caused by technique from step 2 and the distance variability of s = 2.5% caused by green inconsistencies from step 1 were used for the calculation. The players' average distance variability caused by green reading was found to be s = 8.2% of the putt distance.

Step 4: Comparing the Three Different Sources of Distance Variability
The relative importance of each parameter for distance variability was calculated by the following equations:

> Relative importance of green reading = (green reading variability)^2/((green reading variability)^2 + (technique variability)^2 + (green surface variability^2))

> Relative importance of technique = (technique variability)^2/((green reading variability)^2 + (technique variability)^2 + (green surface variability)^2)

> Relative importance of green inconsistency = (green surface variability)^2/((green reading variability)^2 + (technique variability)^2 + (green surface variability^2))

Input to these equations were the measures of distance variability caused by green inconsistency (s = 2.5%, from step 1), technique (s = 6.3%, from step 2) and green reading (s = 8.2%, from step 3).

RESULTS

Average distance variability for the highly skilled players in the "40-putt test" was s = 10.6% of the putting distance. The factors that were estimated to explain distance variability were green reading (s = 8.2%), technique (s = 6.3%) and green inconsistencies (s = 2.5%). The reason why the overall relative distance variability (s = 10.6%) is less than the sum of the variability from the three factors is because variability from green reading, technique and green inconsistencies act independently (in some cases a player can make two mistakes which more or less cancel out each other; e.g., underestimating how fast the ball will roll, and hitting it at lower speed than intended). The relative importance of green reading, technique and green inconsistency are presented in Figure 4.

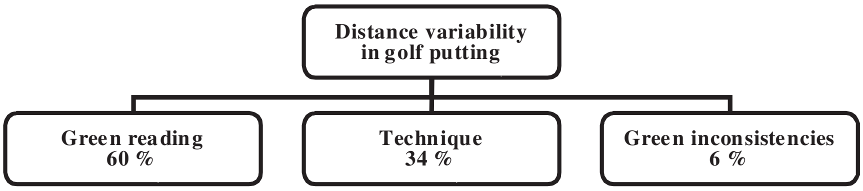

Figure 4. Deterministic Model of Main Results from the Present Study: Relative Importance of Green Reading, Putting Technique and Green Inconsistencies for Distance Variability

DISCUSSION

METHODICAL IMPLICATIONS

Variance analysis in the present study is based on the assumption that the distance variability caused by green reading, technique and green inconsistency are independent variables. It seems clear that distance variability caused by the undetected inconsistencies of the green are independent of the green reading and putting technique variability, due to the fact that the inconsistencies affect the ball roll after the green is read and the ball is hit. It also seems reasonable to assume that technique variability is independent of green reading variability. In this context, the putting technique is defined to start at the moment the player starts to move the putter in the back swing, and it lasts until impact (approximately 1 s). Although it is theoretically possible, it is reasonable to assume that the players during this time did not have any new inputs that could affect their green read for distance throughout the second the technique lasts, especially since the players look at the ball and not at the area they will putt over during the technique performance.

The improvement in distance control over trials in the "30-putt test" has been related to green reading only, and not to improvement in technique. This is based on analysis of the technique variability of 52 elite players (mean handicap = 0.5, s = 2.8) mostly from the study of Karlsen et al. [8], who did between 20 and 30 repeated putts from about 4 m. There was no significant difference in technique variability when comparing the first and second half of the putts in the series. Technique parameters which were assumed to be related to distance control were analysed, and variability and p-values (two-tailed t-test) on the different parameters comparing the first and last half of the putts respectively were: backswing time (s = 35 ms and s = 37 ms, p = 0.27), downswing time to impact (s = 14 ms and s = 15 ms, p = 0.31), backswing time/downswing time to impact (s = 0.12 and s = 0.11, p = 0.51), horizontal impact point (s = 2.6 mm and s = 2.5 mm, p = 0.24), vertical impact point (s = 1.5 mm and s = 1.5 mm, p = 0.89), effective loft (s = 0.38° and s = 0.37°, p = 0.52), rise angle at impact (s = 0.55° and s = 0.59°, p = 0.12), and maximal club head acceleration in downswing (s = 544 mms^{-2} and s = 514 mms^{-2}, p = 0.36). This indicates that improvement over trials in the "30-putt test" was related to green reading and not technique.

Another assumption of the present study is that green reading for distance is perfect after doing 15 trials of the same putt. It is reasonable to think that a highly skilled player is unable to completely understand the read for distance of one specific putt. If so, there would have been some green reading variability in the last 15 trials of the "30-putt test", and therefore the estimated distance variability caused by technique would have been lower, indicating that the importance of the green reading might be even higher than the reported 60% in the present study.

Yet another assumption which the calculations are based on is that the 6-m putt used for the repeated putt test represents the average of all putts in the 40 different putts test in terms of difficulty. This criterion seems to be met since there was no significant difference between the average relative distance deviation of the 40 different putts (8.5%) and the first 6-m putt from the "30 putt test" (9.2%) (p = 0.53). Six metres also corresponded to the median length of the 40 different putts. In addition, the average slopes at the target lines were the same at the two different tests.

Another question is how well the "40-putt test" represents difficulty of tournament play in terms of distance control. Since the "40-putt test" was done on one green, it probably made it easier for the players to read the green for speed compared to a tournament where they play on 18 different greens. For that reason, the importance of green reading for distance variability in the present study might be somewhat underestimated.

IMPLICATION OF RESULTS FOR PUTTING PRACTICE AND RESEARCH

In contrast to what we perceive from instructional articles and elite players' practice schedules, green reading seems to be much more important for distance variability than the technique performance. To the best of our knowledge, no researchers have investigated how green reading should be executed, and we also find that the knowledge of this issue in the practical field is sparse. In contrast, there have been several studies regarding putting technique [3, 8] and we also find the knowledge about technique being relatively good among coaches. This may also be seen in the abundant instruction literature on the swing technique in golf including putting.

We assume it will be beneficial for elite players to give higher priority to green reading in their putting practice. Green reading is a cognitive process where the players have to create an action plan for the motor performance based on the input they get from the green read. It can be suggested that a random practice schedule is beneficial for this because players have to focus more on green reading because they are challenged with a new situation for each trial. This demands that they need to create a new action plan, which in turn may lead to stronger memory representation of the skill resulting in an enhanced learning [9]. A blocked practice schedule might not be equally beneficial, because players can correct the speed of each putt according to the result of the previous putts. This is supported by researchers who have found random practice schedules to be beneficial over blocked schedules for putting among good players [10-12].

Distance-control practice is also a question about how greens should be read. The sequence of obtaining information about slope and distance, and how this information should be used to create an action plan for motor performance, are questions that still have to be answered. In addition, further knowledge about how the relative importance of green reading, technique and green inconsistency is affected by different green conditions is needed. One assumption is that the relative importance of green reading will increase with increased green speed. This is because a given increase in initial ball speed will make the ball travel further on faster greens and thus the distance variability will be higher if the green is fast.

CONCLUSION

Even with the conservative estimates in the present study, it seems that green reading is a much larger determining factor for distance variability than the putting technique, while the inconsistencies of the green only have a small effect. It is suggested that elite players and coaches should focus more on green reading to improve distance control. Knowledge about how we learn to read greens is limited, so further research is needed to gain an understanding which can improve the efficiency of green reading practice and execution.

ACKNOWLEDGEMENTS

The authors would like to thank the Course Manager and staff at Losby Golfklubb (www.losby.no), and the staff at Uppard & Lloyd Golf (www.uppard-lloyd.com) for excellent green preparations and practical help with this project. We would also thank Andreas Hagan for help with the data collection, and for valuable discussions about putting.

REFERENCES

1. Alexander, D.L. and Kern, W., Drive for Show and Putt for Dough? *Journal of Sports Economics,* 2005, 6(1), 46-60.
2. Tierney, D.E. and Coop, R.H., A Bivariate Probability Model for Putting Proficiency, in: Farrally, M.R. and Cochran, A.J., eds., *Science and golf III: Proceedings of the 1998 World Scientific Congress of Golf*, Human Kinetics, Champaign, IL, 1998, 385-394.
3. Delay, D., Nougier, V., Orliaguet, J.-P. and Coello, Y., Movement Control in Golf Putting, *Human Movement Science,* 1997, 16, 597-619.
4. Karlsen, J., Smith, G. and Nilsson, J., Golf Putting: What are the Limiting Factors for Direction Control? Abstract at *Nordic Conference in Motion Analysis*, Oslo, Norway, 2005.
5. Pelz, D., *Dave Pelz's Putting Bible*, Doubleday, New York, 2000.

6. Koslow, R. and Wenos, D., Realistic Expectations on the Putting Green: Within and Between Days Trueness of Roll, *Perceptual and Motor Skills,* 1998, 87, 1441-1442.

7. De Muth, J. E., *Basic Statistics and Pharmaceutical Statistical Applications*, CRC Press, 2006.

8. Karlsen, J., Smith, G. and Nilsson, J., The Stroke Has Only Minor Influence on Direction Consistency in Golf Putting Among Elite Players, *Journal of Sports Sciences*, 2008, 3, 243 – 250.

9. Immink, M.A. and Wright, D.L., Motor Programming During Practice Conditions High and Low in Contextual Interference, *Journal of Experimental Psychology: Human Perception and Performance,* 2001, 27(2), 423-437.

10. Goodwin, J.E. and Meeuwsen, H.J., Investigation of the Contextual Interference Effect in the Manipulation of the Motor Parameter of Over-All Force, *Perceptual and Motor Skills,* 1996, 83(3), 735-743.

11. Guadagnoli, M.A., Holcomb, W.R. and Weber, T.J., The Relationship Between Contextual Interference Effects and Performer Expertise on the Learning of a Putting Task, *Journal of Human Movement Studies*, 1999, 37(1), 19-36.

12. Hwang, G-Y., *An Examination of the Impact of Introducing Greater Contextual Interference During Practice on Learning to Golf Putt,* Part of Doctoral Thesis, Texas A&M University, 2003.

Errata
PhD thesis: “Performance in Golf Putting”
25th August 2010, Jon Karlsen

Page 2, para. 3: …what he ***have*** meant… → ...what he ***has*** meant…

Page 3, para. 2: …outdoor… → … outdoor***s***…

Page 8, para. 3: …players plays on average… → …players play, on average,…

Page 8, para 4: …a reasonable amount of research related to putting is published. → … a reasonable amount of putting research has been published.

Page 10, para. 3: …ball direction ***as***. → …ball direction.

Page 10, para. 3: …from that study, average direction deviation caused by horizontal miss-hits on ten different putter designs was 0.34° per centimeter off center hit. → …from that study, deviation in initial ball direction caused by horizontal miss-hits on ten different putter designs was on average 0.34° per centimeter off center hit.

Page 11, para. 3: They did not conclude on what head movement strategy was most efficient regarding performance. → They did not conclude if any head movement strategy was more efficient than the other regarding performance.

Page 11, para. 4: …***online***… → …***real time***…

Page 12, para. 4: … golfers tested ***which*** were between … → … golfers tested ***who*** were between …

Page 12, para 6: …performance ***is also*** investigated. → … performance ***has also been*** investigated.

Page 12, para 6: …***meter***… → …***m***…

Page 12. para 6: …right dominant players… → … right ***eye*** dominant players…

Page 14, para. 1: … have unevennesses like footprints, grass, mud etc. which will add a certain amount of chance to putting success. → …have unevennesses such as footprints, grass, mud etc. which will change the probability of holing a putt.

Page 15, para. 3: …can also affect how good a putter performs on miss hits. → … can also affect how well a putter performs when contact is not at the “sweet spot”.

Page 15, para. 3: …reduced ***with*** approximately… → …reduced ***by*** approximately …

Page 16. Para. 2: …found that they on average hit the ball shorter with heavier shafts, even thought the… → … found that these golfers, on average, hit the ball shorter with heavier shafts, even though the…

Page 16, para. 3: We experience that the awareness… → It seems, from personal experience, that the awareness …

Page 17, para. 2: …is ***more*** closely studied … → …is closely studied…

Page 17, para. 2: …elite players ***where***… → …elite players ***were***…

Page 18, para. 1: Furthermore, ***som*** new ***methodology*** and equipment ***was*** also specifically... → Furthermore, ***some*** new ***methods*** and equipment ***were*** also specifically…

Page 18, para. 3: …own-developed equipment was… → …and equipment developed in-house were…

Page 22, para. 2: …relevance putting teaching… → … relevance ***to*** putting teaching…

Page 22, para. 4: … important to ***mote*** that … → … important to ***note*** that …

Page 24, para. 2: …circular surface at the size… → … circular surface***,*** the size …

Page 24, para. 5: …to a ***target*** line… → … to a line…

Page 25, para. 1: The slope at the target lines… → The ***average*** slope at the target lines…

Page 25, para. 2: …descriptive methods like means and standard deviations were utilized… → … descriptive methods were utilized to describe the data that were collected.

Page 26, para. 1: The lowest variability was found in a PGA European Tour player, and was 0.28°. → The lowest variability, 0.28˚, was exhibited by a PGA European Tour player.

Page 29, para. 2: …accuracy ***between*** putters… → … accuracy ***among*** putters…

Page 32, para. 1: …***show*** that… → … ***shows*** that …

Page 32, para. 1: …players which were tested with the same methodology… → … players who tested with the same methods…

Page 32, Fig. 12: Negative handicaps are changed to positive handicaps (e.g. "-6" → "+6")

Page 33, para. 1: …***optimums***… → …***optima***…

Page 33, para. 2: …strokes with much face rotation in the downswing could affect consistency negatively… → …strokes with large face rotation in the downswing could decrease consistency …

Page 33, para. 4: … affected consistency negatively… → … negatively affected consistency …

Page 35, para. 3: …which corresponds… → … which corresponds ***closely***…

Page 35, para. 3: It ***also contradicts*** to MacKay… → It ***is also contradictory*** to MacKay…

Page 35, para. 3: … elite players ***were*** different … → … elite players ***was*** different …

Page 35, para. 4: …compensations ***where e.g. a player aim*** left… → …Compensations where***, for example, a player aims*** left …

Page 35, para. 5: … aspects of putting ***like*** green… → … aspects of putting ***such as*** green …

Page 35, para. 5: …this will be addressed… → …This ***idea*** will be addressed …

Page 36, para. 1: …situation ***pose large methodological*** challenges …→ …situation ***posed large logistical and methodological*** challenges …

Page 37, para. 2: Pelz (1989) have done various measures of what percentage of putts he can hole with the True Roller™ from 12 feet (3.7 m). → Pelz (1989) investigated green inconsistencies using the TrueRoller™ on 12' (3.7 m) putts.

Page 37, para. 2: …corresponds to ***an*** direction variability… → …that corresponds to ***a*** direction variability…

Page 38, para. 2 …we ***choosed indirect measures*** to estimate … → …we ***chose to use an indirect measure*** to estimate…

Page 39, para. 2: …are any ***dependency*** between… → … are any ***dependencies*** between …

Page 39, para. 3 … is very high ***for the practical field***, and thus the estimate mentioned above can be justified as long as it is used with ***precaution***. → …is very high ***from a practical perspective***, and thus the estimate mentioned above can be justified as long as it is used with ***caution***.

Page 39, para. 3: …it seems ***like*** green reading… → … it seems ***likely that*** green reading…

Page 39, para. 4: … precision takes longer ***time*** to develop... → …precision takes longer to develop...

Page 39, para. 4: …analysis ***from*** the present data which ***show*** that… → … analysis ***of*** the present data which ***shows*** that …

Page 39, para. 4: …***while*** low handicappers… → … ***yet*** low handicappers…

Page 40, para. 1: … easier to aim with, they actually aimed with less consistency than using blade putters … → … easier to aim with than blade putters, they actually aimed better using blade putters.

Page 40, para. 1: …aiming advantage ***have*** affected… → … aiming advantage ***has*** affected …

Page 40, para. 3: …takes some time. Especially… → … takes some time, especially …

Page 40, para. 4: …differences ***between*** any of … → … differences ***among*** any of …

Page 41, para. 4: … putter design ***have*** relatively … → … putter design ***had*** relatively …

Page 41, para. 4: …using putter ***shaft*** of various… → … using putter ***shafts*** of various …

Page 41, para. 4: …found very ***little*** differences… → ...found very ***few*** differences …

Page 41, para. 5: If there are any positive effect of changing to a better putter it … → If there is a positive effect of changing to a different putter, such a change …

Page 42, para. 1: …differences ***on*** individual level… → … differences ***at an*** individual level.

Page 42, para. 2: …putter aim ,coaching experience shows that distance accuracy is easier to adjust than precision, which takes longer time to develop. → …putter aim, coaching experience shows that distance accuracy is easier to adjust than precision.

Page 42, para. 3: Known to us, no researchers have investigated how green reading of distance/speed should be executed, and we also experience that the knowledge of this issue in the practical field is sparse. → No research has systematically investigated the way green reading and green speed should be taught not how best to evaluate the interactions between them.

Page 42, para. 4: ***Known to us,*** systematic distance errors… → Systematic distance errors…

Page 43, para. 2: …the greens are faster than ***what*** they are used to, the tendency is to put ***to*** far, and opposite if … → …the greens are faster than they are used to, the tendency is to put ***too*** far, and ***the*** opposite if

Page 45, 4th point: …elite players ***aims*** left … →… elite players ***aim*** left …

Page 45, para. 2: …practice should be ***highly prioritized***… → … practice should be ***a high priority*** …

Page 46, para. 1: …could be a player ***which*** in a… → … could be a player ***who*** in a …

I would like to thank Dr. Robert J. Neal for pointing out the above errors.