The SAM PuttLab: Concept and PGA Tour Data

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ABSTRACT
The portable SAM PuttLab uses innovative ultra-sound technology to measure all aspects of a putting stroke with high precision. It is considered that in putting a lack of objective feedback will limit learning and performance. The PuttLab uncovers individual strengths and weaknesses and provides relevant feedback to tailor individual training programs. The PuttLab has been used to collect a reference data sample of 99 PGA Tour players. The data reveals a wide variety of different putting techniques and putting strategies. The common attribute between players is the high consistency of the individual performance. A framework for successful putting is discussed with learning being defined as the search for an optimal solution in the individual motor-workspace, trading off sound technique and high consistency of movement automation.

Key words: Augmented Feedback, Golf, Technology, Movement Variability

INTRODUCTION

Skill acquisition can be defined as the search strategy to identify the perfect solution in the perceptual-motor workspace for a specific motor task; i.e., practice involves repeatedly trying to solve a motor task rather than repeating a particular solution of the task [1]. The role of the coach is to support the student in searching for the best solution in his or her own perceptual-motor workspace.

If learning is the search for an optimal solution of a specific task [1], then the lack of adequate feedback involved in putting is also critical. Although the putting movement is considerably slow as compared with the full swing, the eyes are still not able to follow the putter in detail, i.e. to monitor the face angle through impact. It is also very difficult for a coach to differentiate the various aspects involved for instance

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in direction of the ball, such as misreading the green, misaiming, face errors, path errors, rotation errors, impact spot errors, uneven surface, wind and even dimple errors. For successful motor learning, it is important to provide consistent feedback on the consequences of the motor action independent of random variables involved.

Using technology from the fields of medicine and rehabilitation, the SAM PuttLab has been designed to provide objective, valid and reliable feedback on putting movement. Using data from the PuttLab, individual strengths and weaknesses can be identified. Furthermore, the data can be used to channel the search for appropriate mappings of the perceptual-motor workspace during learning.

To create a reference data sample, data of PGA Tour players' putting strokes has been collected since the year 2003. The data sample is divided into six functional fundamentals of a putting stroke. The reference data is also fed back into the PuttLab to compare the actual performance of a golfer with the average Tour player's performance.

THE SAM PUTTLAB

MEASURING PRINCIPLE

The SAM PuttLab is based on high precision ultra-sound technology. Miniature senders emit high frequency ultra-sound signals to microphones, which are housed in a receiver unit. An infra-red connection synchronizes the process. The travel time of the sound pulses enables calculation of the exact distance between sender and receiver. If three receivers are used, the position of one sender in the three-dimensional space can be calculated. If three senders and three receivers are used, all six dimensions can be reconstructed (i.e., three translational and three rotational). The overall sampling frequency is 210 Hz. The maximum distance of a sender to the receiver is about 1.5 m. The weight of the triplet, which is mounted onto the putter shaft, amounts to 48 g.

The resolution of the system is 0.1 mm and 0.1 degrees. Because of the data smoothing methods applied to the data [2], the resolution of the processed data will be even higher. Tests of accuracy and reliability of the system on putting robots have shown convincing results. Table 1 shows the results for a series of 10 Putts done on a putting robot (Dave Pelz's "Perfy" model [3]). Another test has been conducted on a putting robot and has been described in Nilsson et al. [4]. The results for two series of 20 putts for standard deviation of face angle at impact were quite similar with 0.1° and 0.09°. It should be noted that the results represent the confounding errors of both the PuttLab and the robot itself.

Table 1. Resulting Standard Deviations in a PuttLab Test Conducted With a Putting Robot

Parameter	Standard Deviation
Path Direction at Impact	0.02°
Face Angle at Impact	0.06°
Horizontal Impact Spot on Face	0.3 mm
Shaft Angle at Impact	0.1°
Rise Angle at Impact	0.09°
Lie Angle at Impact	0.05°

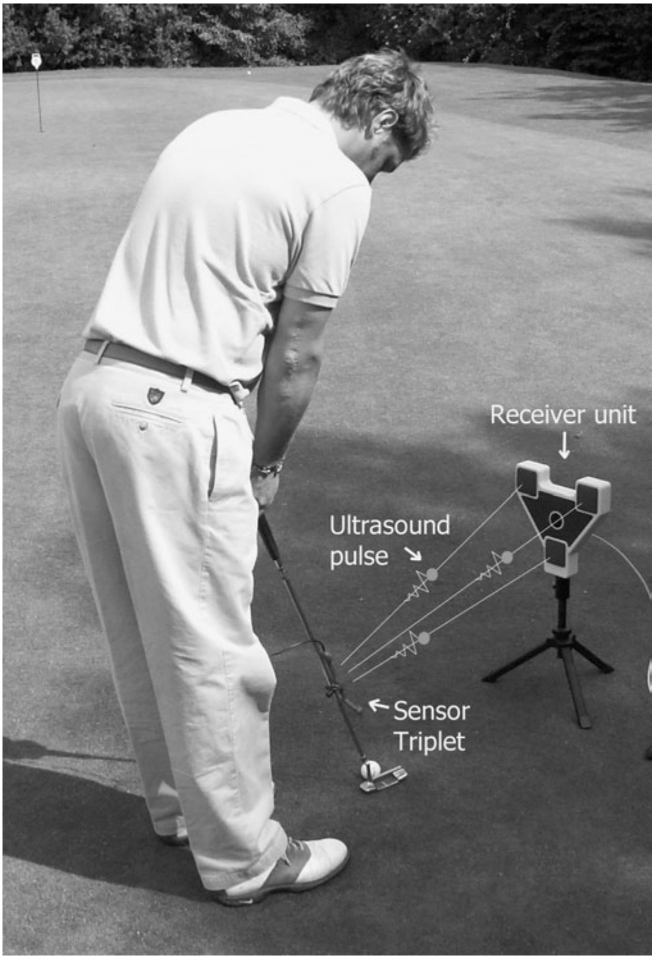

Figure 1. Measurement Principle of SAM PuttLab

An important strength of the system is its high precision and the intrinsic spatial dimension. Because of the nature of sound waves, the signals provide information directly about absolute distances. This is different from video systems where relative size and position information have to be reconstructed from the pixel information into the original three-dimensional space due to complicated calibration routines.

There are two limitations of the ultra-sound measurement principle. During measurement all three sensors have to be 'visible' to all of the three microphones, otherwise the signal is lost. This is normally not a problem in limited movements such as putting. The second limitation arises from the nature of the sound waves. If loud noise or strong wind affects the signal pulses, then the derived position signal will be disturbed.

SYSTEM COMPONENTS

The three sending sensors are integrated in a light T-shaped triplet, which is mounted onto the shaft at a height of 10 inches above the putter face. An additional battery pack is connected through a thin cable with the triplet and contains the power supply for the sensors. The receiver unit contains the three microphones and is placed approximately 50 cm in front of the ball. The receiver unit is connected to a PC through USB and also is powered through USB. During the measurement, all data is transferred to the PC in real-time.

DATA REGISTRATION

After mounting the triplet to the shaft, the system has to be once calibrated for position and direction. A small laser is fixed perpendicular to the putter face and is pointed exactly down the target line. At the same time, the putter is set flat on the surface and touching the ball at the sweet spot. The calibration thus considers ball position, lie angle of the putter, and direction of the target. The physical vertical is calibrated by leveling out a watermark, which is integrated in the receiver unit.

During measurement, the registered data is continuously transferred from the receiver to a PC via USB. The SAM PuttLab software scans the data stream and automatically detects valid putting strokes. A sophisticated data tracker requires a specific sequence of relative positions, movements and timings to identify a valid stroke. The sequence considers: the start position; movement start of backswing; minimum size and time of backswing; direction and maximum speed of backswing; and minimum size, direction, speed and timing of forward swing. If errors in the registered data are detected (i.e., data spikes), then the stroke will be rejected and not stored to file. Putting movements can also be registered without a ball, as long as they start at the calibrated ball position. Practice putts will not be recorded as long as they do not start at the calibrated ball position.

DATA ANALYSIS

To exclude the inherent noise from the signal (random errors), the data stream is smoothed with a filter method that has been specially developed for kinematic analysis of movement data [2]. Reliable data filtering is particularly crucial in calculating the derivatives for velocity and acceleration.

To derive the relevant putting parameters, nine relevant positions are identified in each putting stroke: start of backswing, top of backswing, position of impact, end of forward swing, peak velocity, peak acceleration, peak deceleration, and impact zone 10 cm before and 10 cm after impact. For each position, or between any position, numerous parameters can be calculated, including: face angles, putter path direction and geometry, impact spot, dynamic loft and lie, face rotation, speeds and accelerations, rhythm and timing. Overall more than 60 parameters are calculated for each stroke and stored to file. The resultant parameters can also be exported to any statistical software package for further analysis.

SCORE AND CONSISTENCY

A z-transformation is a mathematical procedure to compare different parameters on a uniform scale by referring the results to the average and standard deviation (SD) of a norm population. The PuttLab uses a norm data sample of 99 Tour players to calculate z-transformed performance ratings for Score and Consistency.

The *Score* rating represents the deviation of the player's average performance from a theoretical *optimal* technical data value. The Score relates to the tendency of a specific movement technique aspect. The optimal data value is either unambiguously defined through the task itself (e.g., square aiming or center-hit spot) or defined by the PGA Tour data sample (e.g., backswing ratio or face rotation). A Score of 100% indicates no tendency and optimal technique. A Score of 75% relates to +- 1 SD of the distribution and thus indicates that about 32% of the Tour players have a technique that is farther away from the optimum.

The *Consistency* rating represents the intra-individual distribution of the single data values for different putts. The Consistency relates to the degree of movement automation or skill level. A Consistency rating of 100% relates to an intra-individual distribution that is 2 SD smaller than the average Tour player's consistency. Only 3% of the Tour players will then have a higher consistency. A Consistency rating of 75% indicates a performance that is equally good as 50% of the Tour players.

DATA DISPLAY

The results are normally displayed in graphical reports, which are defined in programmable macro-files. The reports can present the data in any arrangement and on different levels of complexity and detail. Reports can contain the putter in a specific view, numerical data values for average and standard deviation, Score and Consistency ratings, bar graphs for single data values, and time courses of specific variables. Additionally, reference values from the Tour data sample are directly included in the reporting. The bar graphs contain gray shaded areas, which correspond to a distribution of one standard deviation of the Tour player's performance.

Data tables can contain numerical values for each single putt, the average values and standard deviations. Tables are very helpful to provide more specific information as needed, e.g., for putter fitting. Competence profiles allow display of Score and Consistency values in a bar graph style. Up to ten different measurements can be directly compared inside one colour-coded competence profile. Competence profiles are a concise way to compare a particular player with a reference player, to document before/after trainings effects, or to directly compare the performance of different putters. In the 2D/3D replay mode, the movements of the putter can be replayed with a stick figure graph in different views and speeds. Using the keyboard, the display can also be scrolled frame by frame.

TRAINING MODE

A powerful feature of the PuttLab is the real-time feedback of performance. The screen display in the Training Mode is very similar to the graphical reports. For each putt, the result is displayed graphically and numerically on the screen. Different screens are available for all relevant parameters and can be accessed by key press. The effect of any change on the putting stroke can be directly displayed and objectively evaluated. So as to avoid interrupting the on-going movement, we use terminal feedback or knowledge of results (KR) feedback, which is only presented after completion of the task.

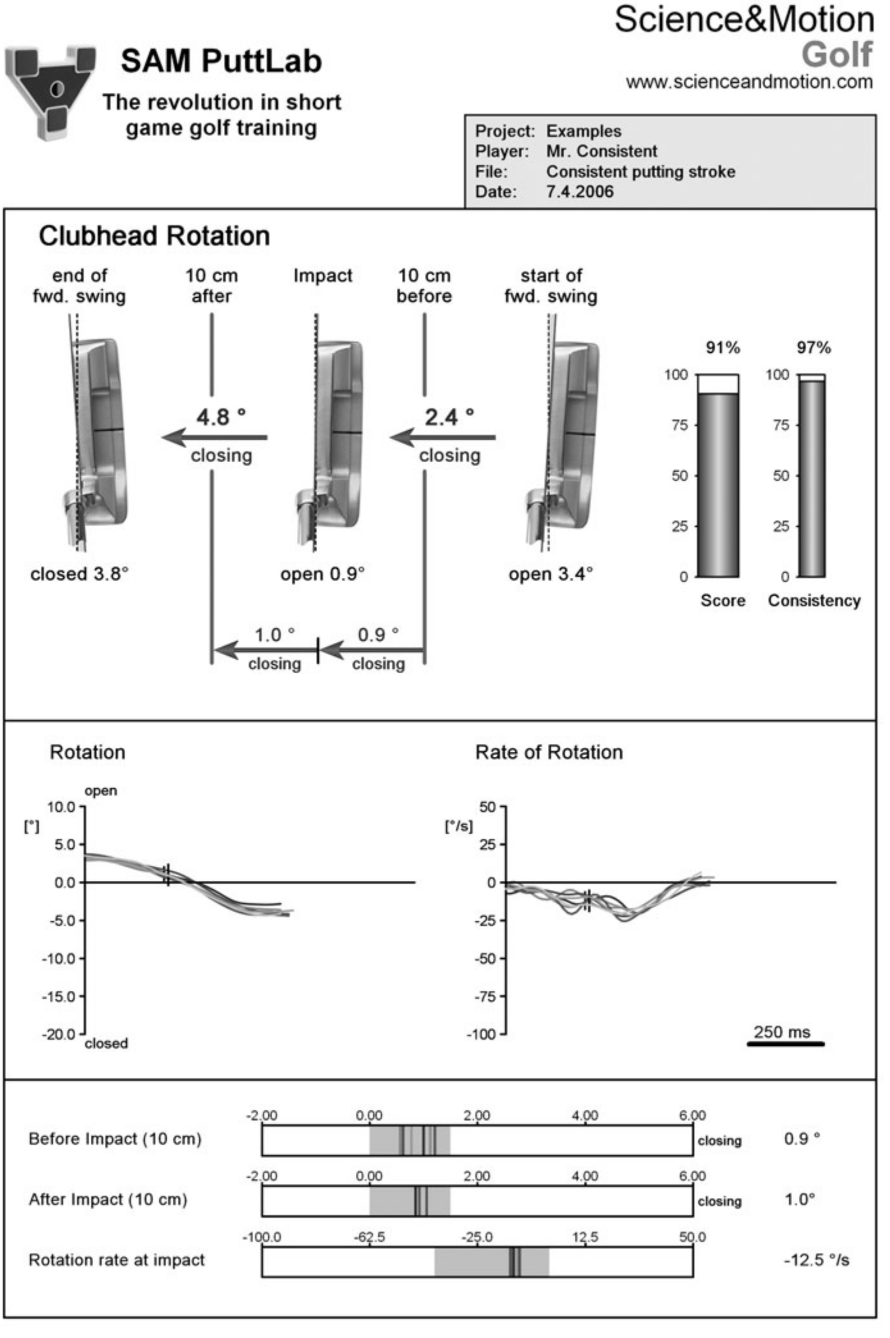

Figure 2. Example of SAM PuttLab Report

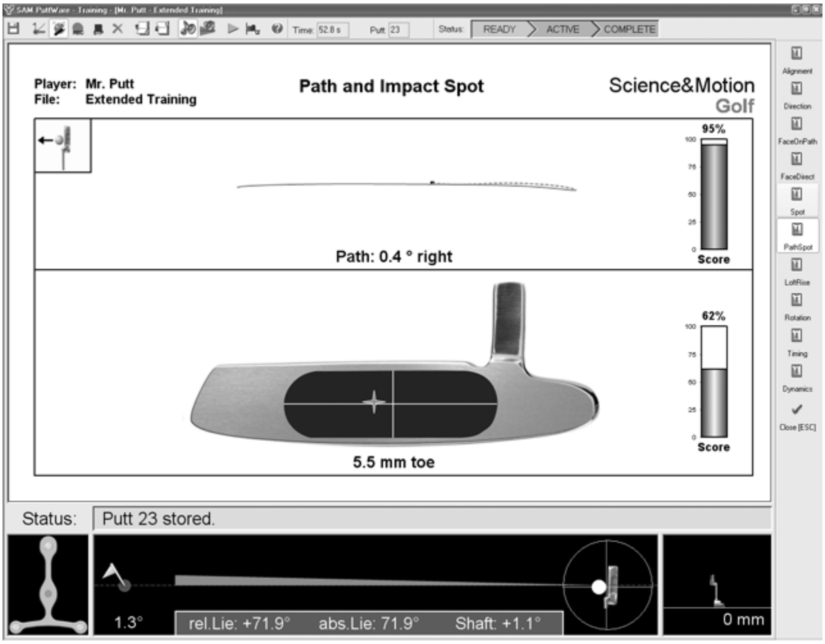

Figure 3. Example of SAM Putt Lab Training Screen

DATA FROM THE PGA TOURS

In this section, relevant statistics of our PGA Tour data sample will be presented. Since 2003 the PuttLab has been used on PGA Tours in order to measure the putting strokes of PGA Tour players. The data sample presented in this article represents data of 99 male PGA Tour players measured at 9 PGA tournaments (eight PGA European Tour and one USPGA Tour events) between 2003 and 2005. The average greens-in-regulation (GIR) putts per round for the sample in 2004 was 1.79 (range, 1.72 to 1.87), the average putts per round were 29.6 (range, 28.3 to 31.1) and the GIR putt ranking was 67.4 (range, 4 to 147).

For the measurement, a straight and level putt of 4-m length was selected on the practice green. On slower greens, the distance was slightly reduced. The reference was a putter speed at impact of 1.5 m/s. Before calibrating the target direction with a laser pointer, the players were allowed to have some practice putts. The players had to confirm that they considered the putt as being straight otherwise the target direction was slightly adjusted. Some of the players then decided for a calibration to the right edge of the hole instead of the center. Although face and path angle refer directly to the absolute calibration, it should be noted that the relative face-on-path parameter is independent of the calibration. The players were instructed to run through their complete pre-shot routine before each putt and they were asked to use their own putter. Seven consecutive putts were recorded for each player.

One limitation of this study is the fact that the data has been captured at different tournaments. Although we tried to always select a similar putt, there is no control of absolute environmental conditions. The most important factors were to select a straight, level putt and to adjust the distance. Nevertheless, some of the parameters we measured might be more dependent on the different conditions than others and this might explain some of the variance found in our data. For example, the speed of the green might directly influence the effective loft and rise angle that the players apply to the ball in order to alter launch angle and spin rate. However, most of the parameters we measured can be assumed to be sufficiently independent of the conditions.

The data was analyzed with the scientific module of the SAM PuttLab software. For each putt, a graphic report was printed to control the reliability of the results. We then extracted the most relevant parameters from a total set of 60 parameters per putt and categorized these parameters into functional groups. We identified six groups of independent parameters, which represent the six fundamentals of a putting stroke. Table 2 lists the results for the sample of 99 players, the corresponding standard deviations (SD) and the results for intra-individual performance, which is the repeatability or the consistency of the seven putts recorded.

Table 2. Putting Statistics for a Sample of 99 PGA Tour Players: Group Average Value, Corresponding Group Standard Deviation (SD) and Individual SD (Consistency) for Each Player's 7 Putts

Parameter	**Group Average**	**Group SD**	**Consistency**
Face Angle at Address	0.35 ° Right	1.56 °	0.67 °
Face Angle at Impact	0.30 ° Right	0.59 °	0.70 °
Putter Path Direction at Impact	0.80 ° Left	2.24 °	0.83 °
Face on Path at Impact	1.10 ° Open	2.76 °	0.70 °
Backswing Length (BSL)	241 mm	38 mm	10 mm
Path Symmetry (BSL/FSL)	0.36	0.05	0.02
Horizontal Impact Spot	1.56 mm Toe	3.5 mm	2.1 mm
Vertical Impact Spot	4.9 mm Up	2.2 mm	1.4 mm
Face Rotation in Impact Zone	3.2 °	1.0 °	0.34 °
Dynamic Shaft Angle	0.0 °	1.2 °	0.49°
Vertical Angle of Attack (Rise)	2.8 °	Up 1.8 °	0.60°
Backswing Time (BST)	670 ms	90 ms	30 ms
Time to Impact (TI)	317 ms	35 ms	11 ms
Forward Swing Time (FST)	820 ms	100 ms	45 ms
Backswing Rhythm (BST/TI)	2.1	0.29	0.11
Impact Timing (TI/FST)	0.39	0.04	0.02
Impact Speed	1510 mm/s	119 mm/s	45 mm/s

Notes: Path Symmetry: Ratio of backswing to forward swing path length. Vertical Impact Spot: Corresponds to a standard height of the putter of 2.5 cm. Impact Zone: +- 10 cm before and after impact position. Shaft and Rise Angle: As viewed from the frontal plane. Start of the Backswing at putter acceleration of 0.6 m/s^2. Backswing Rhythm: Ratio of backswing time to time to impact. Impact Timing: Ratio of time to impact to forward swing time.

THE SIX FUNDAMENTALS OF A PUTTING STROKE

AIMING

The average of the Tour players for aiming the putter face is slightly right by 0.35°. What is quite surprising is the wide distribution of aiming over the group. The SD of 1.56° indicates that more than 55% of the players aim to a target outside of the hole on a straight 4-m putt. The average consistency of each player is 0.67°.

We did not find any correlation between accuracy of aim and SD of face angle at impact (Pearson correlation $r = 0.07$, $p > 0.01$). But we found a significant correlation between SD of aim and SD of face at impact ($r = 0.62$, $p < 0.01$) and SD of path direction at impact ($r = 0.47$, $p < 0.01$). From these results, we conjecture that the consistency of aim seems more important for consistent ball direction than the average direction of aim for elite players. This does not mean the accuracy of aim is of no importance, but rather that accurate aim seems only of value if it can be repeated consistently.

DIRECTION

The direction of the ball is basically determined by the angle of the putter face and the direction of the putter path at impact. Following Petz [3], it is generally assumed that the contribution of face angle to resulting ball direction is 82% with the contribution from the path being only 18%. Off-center hits can also influence ball direction if the impact spot is outside of the sweet spot. Recent putter technology reduces this problem by increasing the moment of inertia (MOI) of the putters.

On average, the Tour player hits the ball with a slightly open face of 0.3°. The group SD is now reduced to 0.59°, which means that deviations in aiming are normally corrected by impact. The average path direction at impact points 0.8° to the left, thus in the opposite direction than the face. The compensation of an open face on a path pointing to the left allows the ball to still go straight. On average, the Tour player's putter face is 1.1° open relative to the putter path at impact. The group SD of the path direction at impact is 2.24°, which is higher than the SD of the face angle at impact.

In order to calculate the true effect of errors on ball direction, however, it is necessary to multiply the group SD by the effect on direction; i.e. for face angle, 0.59° x 82% = 0.48°, and for putter path, 2.24° x 18% = 0.40°.

The consistency of the path at impact is 0.83° and slightly less than the consistency of the face at impact with 0.7°. Again, we can calculate the resulting contribution to ball direction consistency. Effective face angle consistency is 0.7° x 82% = 0.57° and effective putter path consistency is 0.83° x 18% = 0.15°. This means that the effective consistency of putter path is 3.8 times higher than effective consistency of face angle.

PATH GEOMETRY AND IMPACT SPOT

Inside the impact zone, the swing path of the putter should run parallel to the target direction, but it can behave differently at the beginning and end of the swing. Most players show a swing path that is arced to the inside on the backswing and on the follow through. This ellipse is a consequence of naturally swinging the putter in a tilted swing plane and also corresponds to some amount of face rotation (see below).

The length of the backswing is found to be considerably shorter than the length of the follow through. On average, the backswing is only 36% of the forward swing length with a group SD of 5%. This means that the swing path geometry is significantly not centered to the ball. Accurate length of the swing path is particularly important in putting with regard to keeping timing constant. Length of the backswing will then directly define the speed of the putter at impact and thus length of the putt. The consistency of backswing length in each player is 10 mm at an average backswing length of 241 mm.

The geometry of the putter path also determines the resulting impact spot. If backswing and forward swing path are congruent, then the impact spot will exactly meet the spot where the ball was aimed at. If the swing path crosses inside or outside through impact, then the aiming and impact spots will be different. Inconsistent swing planes will also result in inconsistent impact spots. The average horizontal impact spot is at an almost neutral position of 1.56 mm at the toe with a group SD of 3.5 mm. Consistency of impact spot is also high with 2.1 mm.

FACE ROTATION

Natural face rotation is a result of moving the putter on a tilted swing plane. The more tilted the plane is, the more the face will rotate relative to the target line. Many players believe that the face is actively opened or closed. Relative to the swing plane, however, the putter is always square to the movement path if naturally moved back and forth. It is only because the swing plane is tilted that the projection of the putter path to the target line appears as an ellipse and the putter face then opens and closes relative to the target line. While some players over-rotate the putter by breaking the wrists through impact, other players try to reduce rotation by counteracting the natural behavior of the putter (i.e., they close the face in the backswing and open the face through impact).

The Tour data reveals that inside of the impact zone of 10 cm before and 10 cm after impact the putter face is closed 3.2°. The group SD is wide with 1.0°. Each player's consistency for face rotation is 0.34°. The overall rotation in the forward swing amounts to about 10°. There is no smooth zero rotation found in Tour players. Only a few players tend to not rotate the putter in the forward swing. A more detailed analysis shows that these players do not reduce rotation by swinging on a more vertical swing plane, but rather re-open the putter through impact.

LOFT AND RISE

In general, the launch angle of the ball and the spin rate are determined by the effective loft applied to the ball and the rise angle of the swing path through the ball. We did not measure the static loft on the putters, thus our data refers to the angle of the shaft only. The effective loft amounts to shaft angle at impact plus static loft. Positive effective loft imparts backspin to the ball, whereas an upwards stroke through impact imparts some amount of 'topspin' to the ball. The effect of loft and rise on launch angle are quite comparable to the effect of face and path on ball direction. Loft (face) will contribute far more to the resulting launch angle as compared with rise angle (path).

The average dynamic shaft angle at impact is neutral with 0.0°. However, the wide group SD of 1.2° indicates that many players are delofting the putter. Others are adding loft with a hand position behind the ball at impact. The behavior of rise angle is also not homogeneous with an average angle of 2.8° upwards and a group SD of 1.8°. As most of the putters we measured showed a static loft between 3° and 4°, the launch conditions will differ between these players. Many players apply a delofted face to the ball with an upstroke, resulting in a flat launch angle and considerable 'topspin'; whereas other players are adding loft at a more level impact, which results in a steeper launch angle and backspin to the ball. As a consequence of our analysis, some players ended up reducing the static loft on their putter. As soon as there is a common consensus of the preferred launch conditions available, the PuttLab data could be used in conjunction with video analysis of launch angle and spin rate in order to tailor the putter exactly to the needs of the player.

MOVEMENT DYNAMICS

The movement dynamics data directly reflect the organization of the movement itself and are represented by velocity and acceleration signals. The biggest differences in the acceleration signals of the Tour players are found between the top of backswing and impact. We categorized the course of acceleration into three stroke types. The results are displayed in Table 3 and show that 47% have 'swing'-type strokes, 23% have 'hit'-type strokes, and 30% have an intermediate type of stroke. Due to the fact that the speed of the putter changes rapidly at impact, accurate movement timing is mandatory for players using a 'hit'-type stroke.

Table 3. Classification of Stroke Types Due to Acceleration to Impact

Stroke Type	Acceleration	Percentage of Players
Swing	Constant Inside of 10%	47 %
Intermediate	Increasing	30 %
Hit Steep	Ascending 100%	23 %

Backswing time is on average 670 ms, with a group SD of 90 ms; time to impact is on average 317 ms, with group SD of 35 ms; and time to complete forward swing is 820 ms, with group SD of 100 ms. The high numbers for SD show that the absolute times differ widely between players. The consistency of the swing time is high, especially for time to impact (11 ms). Consistency of impact speed of the putter head is also high with 45 mm/s at an average impact speed of 1570 mm/s.

Backswing rhythm and impact timing describe the relations between the different swing times. Rhythm and timing are ratios that can be similar, even for players with very different swing tempos. The average backswing rhythm (backswing time divided by time to impact) is 2.1, with a group SD of 0.29. Average impact timing (time to impact divided by forward swing time) is 0.39, with a group SD of 0.04. This means that the ball is hit early in the stroke before maximum putter speed, thus ensuring a smooth acceleration through impact.

DISCUSSION

We found that ultra-sound technology is suitable for accurate measurement of putting movements. The system is easy to use, portable and can be used indoors and outdoors. Data capture takes only about 5 minutes and the reports immediately provide objective information on relevant details of the putting strokes. Video systems need some complicated calibration routines to allow translating the pixel information into real physical measures. Marker-based systems are still considered to be state-of-the-art technology in movement analysis especially with regard to precision. An ultrasound system using a fixed-marker configuration is additionally easy for calibration and handling purposes. Tests on several putting robots have confirmed the outstanding accuracy of the PuttLab.

A limitation of using the PuttLab outdoors is that strong wind can make it impossible to register consistent data. Another limitation might be the weight of the sensor triplet added to the putter, but few players have expressed any negative feelings about the increased weight on the shaft. The added weight might change the swing characteristics of the putter. As the triplet is mounted close to the balance point on the shaft, however, the swing weight will not be affected too much. Interestingly, we more often got positive feedback on two other consequences of the triplet on the shaft: Some players reported that the swing felt smoother and others reported that impact resulted in less vibration of the shaft.

In the PuttLab Training Mode, objective information is provided to channel the search for an individually optimal solution for the task of putting [1]. We do not use concurrent feedback where the information is continuously fed back during the execution of the movement. Based on the results of research on skilled handwriting, visual, closed-loop feedback in automated movement execution is detrimental to smooth movement dynamics and should only be used in very early stages of learning [5]. The PuttLab uses terminal feedback and knowledge of results (KR) feedback, which is only presented after completion of the task. The PuttLab also allows the complexity and the frequency of augmented feedback to be modified in accordance with the skill level of the learner and the difficulty of the task [6].

The goal in putting could be simply described as bringing the putter to impact square to the ball on a path pointing exactly to the target line at an adequate putter speed. Surprisingly, the Tour data generally show that there is no such model putt. In contrast, a wide variety of different putting techniques was found with open or closed putter face, straight or curved swing paths, different path lengths, different levels of face rotation, ‘hit’- or ‘swing’-type strokes, and fast or slow swing tempo. Our data does not represent a model putt, but rather a framework within which an individual solution should lie. The different techniques are not directly related to the ranking of the players. There can be several reasons for this variety of putting techniques, e.g., different physical conditions of the players, different putters used, or different technical and psychological approach. Other reasons might be the discrepancies in the current training concepts and the lack of objective feedback during practice.

Regarding face rotation, we found that the average Tour player is rotating his putter about 10° inside of the forward swing. This does not concord with the ‘straight back-straight through’ stroke concept forwarded by Pelz [3]. Some amount of face rotation could also be explained by the use of misfit putters. If we fit putters to an adequate length, we normally end up shortening the shaft by between 1 and 2 inches. As a consequence of the less upright posture and the more vertical swing plane, the face rotation was sometimes immediately reduced to 50%. Our data also suggests there is wide variation in effective loft and rise angle at impact. There will thus be wide variation in effective launch angle and spin rate between the players, which has to be individually controlled and adjusted. More generally, the putter can be seen as a task-specific constraint that might widely influence learning and performance. A misfitted putter will thus result in a sub-optimal solution for the task. The different types of putters used by the Tour players, as well as misfitted putters, may explain some of the variance in our data sample from Tour players. We are in the process of developing a SAM PuttLab putter-fitting protocol that trades off both aspects of neutral technique and individual preferences.

Most of the Tour players show one common characteristic in their strokes – a very high repeatability of their individual movement pattern, which is described by the Consistency score. At the same time, many elite players seem to accept a limited amount of tendency in their technique. A small amount of tendency might even facilitate greater consistency through greater reliance on movement instincts. The best individual solution might differ from a theoretical technical optimum in a certain workspace.

Although swing time varies widely among elite players, many players exhibit a backswing rhythm (ratio of backswing time to time to impact) that is very close to the average ratio of 2.1. For example, Tiger Woods shows a rhythm of 2.2, with a backswing time of 660 ms; whereas Loren Roberts shows exactly the same rhythm of 2.2, but with a backswing time of 977 ms.

Generally, we found a distinction could be made between feel and technical players. *Feel* players report that they don't really care about their putting technique. Very often these players did not want to be measured on the PuttLab, because they were afraid of being flooded with technical thoughts. If we measure feel players, they normally show very high consistency in their strokes but also a certain amount of tendencies and compensations. Also for feel players, it would make much sense to neutralize the stroke as much as possible without reducing the amount of consistency. *Technical*-oriented players have minimized their tendencies, but often show reduced consistency. The technical players like the PuttLab and want to know every detail of their putting stroke. Reducing the technical thoughts and allowing the body to more intuitively act immediately increases the consistency in these players. In technical players, we often work on movement aspects like rhythm or smooth face rotation. The balancing out between the two contradictory aspects of control (technique) and movement (feel) appears to be crucial.

Another important finding relates to the face rotation through impact. There are many discussions about the correct amount of face rotation, but the consistency of face rotation is rarely considered. Often face rotation is not understood as a natural consequence of moving the putter on an inclined swing plane. Face rotation is often interpreted as being detrimental to the stroke. We found many players who tend to manipulate the putter face to reduce rotation or to block the face square through impact. Blocking the natural behavior of the putter face is disturbing the smoothness of the stroke and is reducing consistency of face rotation. There is another implication lurking behind blocking of face rotation. In our data, the yips can be typically identified as an involuntary twitching and jerking of the putter face induced by the right hand. This shows up in irregular and large oscillations of face rotation around impact. The oscillations found in mild forms of the yips look very similar to the rotation signal if there is a blocking of face rotation through impact. In some of the players, the blocking strategy already resulted in remarkable and inconsistent oscillations. Our data on face rotation provides evidence that there is a continuum between (subconsciously driven) manipulations of the putter face at impact and the development of the yips. Data collected using the PuttLab can uncover the tendency for a player to develop the yips. Interestingly, the golfers we identify as being at risk of the yips before outbreak normally do not show signs of anxiety and stress which is often reported as being the cause for developing the yips. Contrary to a recent review of the literature [7], the anxiety related to yips could more be a consequence of the problem rather than the true cause of it.

CONCLUSION

The aim of this article was to provide objective data on the putting strokes of PGA Tour players. Although the results are limited in reliability due to the varying environmental conditions at different venues, there is still a wealth of information that can help us to better understand the processes involved in successful putting. Insights into the yips provided by data on putter face rotation shows the potential value of the SAM PuttLab for multi-disciplinary research in the science and psychology of putting.

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