Validity and reliability of a new method for measuring putting stroke kinematics using the TOMI® system

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Abstract

The purpose of this study was to determine the validity and reliability of a new method for measuring three-dimensional (3D) putting stroke kinematics using the TOMI® device. A putting robot and a high-speed camera were used to simultaneously collect data for the validity evaluation. The TOMI® device, when used in conjunction with standard 3D coordinate data processing techniques, was found to be a valid and reliable method for measuring face angle, stroke path, putter speed, and impact spot at the moment of ball contact. The validity of the TOMI® measurement system was quantified using the 95% limits of agreement method for each aforementioned variable. The practical significance of each validity score was assessed by incorporating the maximum estimated measurement error into the stroke of the putting robot for 10 consecutive putts. All putts were executed from a distance of 4 m on a straight and flat synthetic putting surface. Since all putts were holed successfully, the measurement error for each variable was deemed to be negligible for the purposes of measuring putting stroke kinematics. The influence of key kinematic errors, at impact, on the outcome of a putt was also determined.

Keywords: *Golf, putting, validity, reliability, Bland-Altman*

Introduction

According to the Professional Golf Association (PGA) Tour statistics, the putting stroke accounted for 40% of all strokes made during tournament rounds of golf in 2008 (PGA Tour, 2009a, 2009b). This is in agreement with Alexander and Kern (2005), who found that putting ability was the most important skill in determining earnings on the PGA Tour. To hit a successful putt, a golfer must correctly read the green to determine the optimal speed and direction (target line) with which to project the ball. The golfer should then execute a putting stroke where, at impact, the putter head has only horizontal velocity in the direction of the target line, and the plane of the putter face is perpendicular to that line (MacKenzie & Sprigings, 2005). The putter head must also be travelling with the appropriate speed and contact the ball at the centre of the face to impart the optimal amount of momentum to the ball (Pelz & Frank, 2000). Based on previous research (Karlsen, Smith, & Nilsson, 2008; Pelz & Frank, 2000) and applying Newton's Laws, a specific set of four variables, under the control of the golfer, can be identified as the main deterministic factors in the

outcome of a putt: face angle, stroke path, putter speed, and impact spot. At the moment of ball contact, these variables primarily determine the initial velocity of the ball.

According to Hume and colleagues (Hume, Keogh, & Reid, 2005), few studies have been conducted on the biomechanics of the putting stroke. Most previous studies on putting performance have focused on the final result of the stroke, such as the number of putts sank or the position the ball finished relative to the hole (Aksamit & Husak, 1983; Carnahan, 2002; Coffey et al., 1990; Gott & McGown, 1988; Hardy, Mullen, & Jones, 1996; Ishikura, 2008; Meacci & Pastore, 1995; Thomas, Neumann, & Hooper, 2008; Vickers, 1992). There has also been a focus on measuring the face angle of the putter at address, just prior to execution of the putting stroke (Coffey et al., 1990; Karlsen & Nilsson, 2008; MacKay, 2008; McGlynn, Jones, & Kerwin, 1990; Pelz, 1994; Potts & Roach, 2002). However, relative to measuring face angle at address, measuring the putter head kinematics at impact provides a clearer indication of the golfer's putting skills. For example, assuming the read of the green

was correct, if the ball misses the hole on a straight putt it could have been the result of an error in face angle, stroke path or impact spot. Most researchers who measured putter kinematics during the stroke limited their analyses to two-dimensional (2D) displacement and velocity measures (Craig, Delay, Grealy, & Lee, 2000; Delay, Nougier, Orliaguet, & Coello, 1997; Fairweather, Button, & Rae, 2002). Lee and colleagues (Lee, Ishikura, Kegel, Gonzalez, & Passmore, 2008) collected three-dimensional (3D) coordinate data, but only determined the position and not the angular orientation of the putter during the stroke.

To measure the four aforementioned deterministic variables at impact, the researcher must collect 3D kinematic data of the putter's motion. Typically, this would require an expensive optical recording system that would automatically record 3D positional data for each putt (Lee et al., 2008). Researchers could also configure their own systems using multiple cameras and employ the common Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971), which has been used by researchers to study the full swing (Coleman & Rankin, 2005; Neal & Wilson, 1985). Although less expensive, it requires more data-processing time primarily due to digitizing the coordinate points. This becomes time prohibitive when one considers the large number of trials in a typical putting study (Karlsen et al., 2008).

Recently, systems have been designed specifically for analysing putting kinematics. For example, Karlsen et al. (2008) used the SAM PuttLab® (Science&Motion, Munich, Germany) to examine the influence of the putting stroke on directional consistency. Karlsen et al. tested the ability of the device to reliably measure face angle at impact using a pendulum putting rig. They concluded that the device was reliable for measuring face angle based on standard deviations of 0.09° and 0.10° for two sets of 20 identical putts. The validity and reliability for measuring the other deterministic impact variables (stroke path, putter speed, and impact spot) were not assessed. Recently, researchers have also used the SAM Puttlab® to measure the 3D kinematics of the putting stroke for the purpose of investigating the "yips" (Filmalter, Noizet, Poppel, & Murthi, 2008; Marquardt & Fischer, 2008). Filmalter et al. (2008) did not report on the validity or reliability of the SAM Puttlab® in their study.

A similar motion analysis system, TOMI® (Pure Motion, Inc., Southlake, TX), has also been developed for analysing the putting stroke in real time. While more affordable, TOMI® was not initially developed for use in a scientific research setting. The "Pro" version of TOMI® can be set to output the raw 3D data collected during the stroke into an electronic spreadsheet file. This permits researchers to use a simplified and affordable data collection system with the freedom of performing their own calculations with the raw data. However, the validity and reliability of this measurement method for analysing putting kinematics has not been assessed. Therefore, the main aim of this study was to evaluate the validity and reliability of the TOMI® system for measuring the 3D kinematics of the putting stroke. A secondary objective was to determine the importance of key kinematic errors, at impact, on the outcome of a putt.

Methods

Operational definitions

To operationally define the four deterministic variables, an inertial frame of reference is useful. The positive X-axis extends from the centre of the putter face along the intended initial direction of the putt and is coincident with the target line. The positive Y-axis extends vertically up from the ground and the positive Z-axis is formed according to the right-hand-rule (Figure 1a). Face angle is defined as the angle
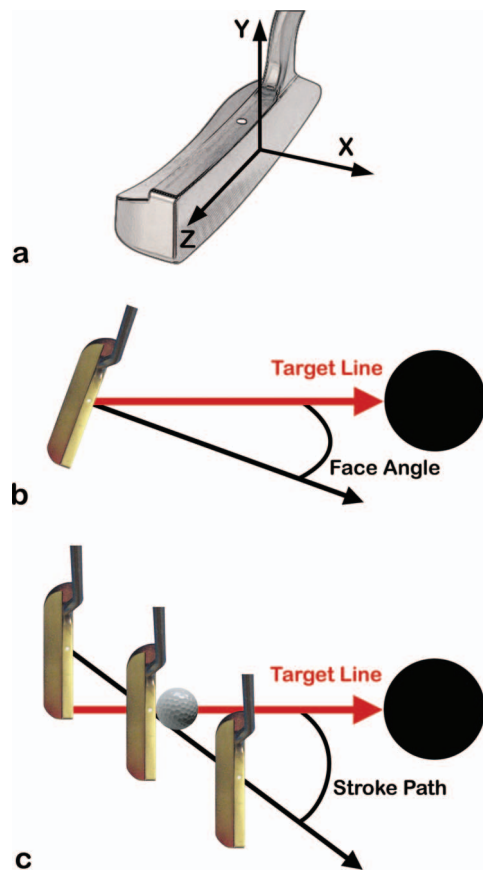

Figure 1. (a) Inertial frame of reference. (b) Face angle measurement convention. (c) Stroke path measurement convention.

formed between the target line and a line perpendicular to the putter face (Figure 1b). Stroke path is defined as the angle between the velocity vector of the putter head and the target line (Figure 1c). Putter speed is defined as the velocity of the centre of the putter face along the X-axis (target line). Impact spot is defined as the distance from the centre of the putter face to the ball contact point, along the heel–toe axis of the putter. All four variables are measured at impact. The origin of the reference frame is a theoretical position located at the centre of the putter face when the centre of the putter face is flush with the ball and both face angle and impact spot are zero.

Instruments

TOMI®. The TOMI® system consists of a battery-charged clip, comprising four light-emitting diodes (LEDs), which attaches directly to the putter shaft (Figure 2). A nearby camera receives information from the LEDs about their coordinates in 3D space and relays it to a computer. With the use of a laser, the TOMI® system is calibrated by placing the putter head flush with the ball in the address position with the putter face square to, and centred on, the target line. The system captures the coordinates of the LEDs in the calibrated position. The real-time stroke variables reported by TOMI® are based on a sampling rate of 30 Hz, which limits the ability to capture the moment of impact (MacKay, 2008). However, the raw 3D coordinate data from each LED are stored in a data file immediately after each stroke with the top line of each stroke data file

containing the LEDs' coordinates in the calibrated position. This permits researchers to process the raw data using their own methods, such as those described later in this article.

Putting robot and environment. A proprietary golf robot was designed and built, in a university machine shop, with the help of a machinist with 25 years of experience. The robot design allowed for the stroke path, face angle, lie angle, and backswing length to be set independently (Figure 2). The constrained pendular motion of the robot ensured that the address position of the putter was identical to the impact position. Lasers positioned on the putter face and robot stand indicated the face angle and stroke path of the putter, respectively. The putting robot, when used in conjunction with the procedures described later, generated identical putting strokes with known stroke paths and face angles at impact. All putts were executed with a Nike Unitized Retro Putter, 0.89 m (35 inches) in length, on a synthetic putting surface that was 7 m long and 5 m wide. The surface was nominally flat and had a Stimp reading of 3.5 m ($\sim$11.5 feet).

High-speed camera. A high-speed camera (SportsCam Model SC500ME, Fastec Imaging, San Diego, CA) was used to measure the putter head speed and impact spot of putts executed by a live golfer for the purpose of validating the TOMI® system. An explanation for the use of a live golfer, in lieu of the robot, is provided below in the sub-section entitled "Validity: putter speed and impact spot". Approval for the study was granted by the St. Francis Xavier University Research Ethics Board.
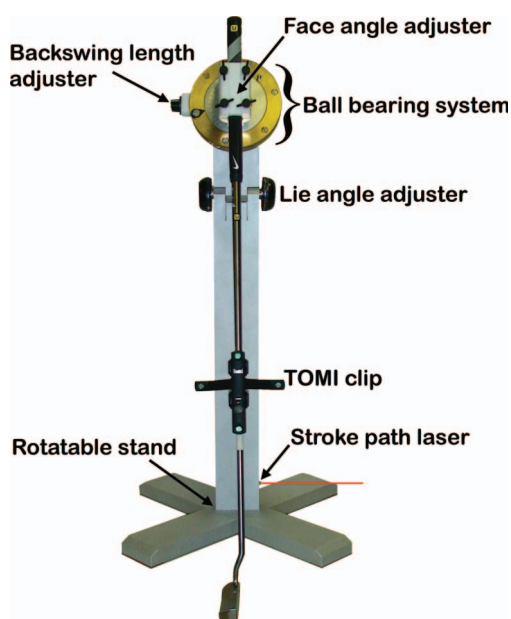
Processing of the raw coordinate data

A customized program, written in Matlab (R2007a, The Mathworks, Inc., Natick, MA), filtered, up-sampled, and transformed the raw data into the necessary form for calculating face angle, stroke path, putter speed, and impact spot. The data were filtered with a fourth-order zero-lag low-pass Butterworth filter at a cut-off frequency of 8 Hz. The highest frequency content of a putter's displacement signal is below 15 Hz, which is typical of most human movement (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). This was confirmed, before filtering, by determining the discrete Fourier transform for the three linear, and three rotational, degrees of freedom of the putter head. Several strokes from both the robot and live golfer were analysed. Inspection of the power spectral density plots revealed virtually no power above 10 Hz. This was true for all three linear displacements, and all three angular displacement signals. Since the raw

Figure 2. The putting robot allowed for the stroke path, face angle, lie angle, and backswing length to be set independently.

displacement data were collected at 30 Hz, which is more than twice the highest frequency in the signal, the sampling theorem ensures that the signal is completely represented in the frequency domain. This means that the raw displacement data can be expressed in the frequency domain and subsequently digitally resampled at a sufficient rate in the time domain (Hamill, Caldwell, & Derrick, 1997). This permitted the raw coordinate data from each LED to be resampled at 1000 Hz, which allowed for the precise measurement of each variable at impact. Knowing the lie angle of the putter and 3D position of the LED clip relative to the centre of the putter face allowed the global inertial reference frame to be created based on the calibrated position of the putter (Figure 1a). The coordinates of the centre of the putter face in the calibrated position were (0, 0, 0). The precise moment of impact was determined by finding the instant in the putter head's trajectory (now sampled at 1000 Hz), which was closest to the calibrated position (0, 0, 0).

Procedures

Validity: face angle and stroke path. The face angle and stroke path of the putter, at impact, were predetermined using the putting robot and two associated lasers, which were projected onto a wall that was inscribed with a grid. The distance between the putting robot and the grid was 6.71 m. The grid was composed of major lines every 10 cm and minor lines every 0.5 cm. Right angle trigonometry reveals that from 6.71 m away, a 0.5-cm change in the laser projection on the grid is equivalent to a $0.04°$ change in angle. Both face angle and stroke path at impact were systematically varied over a series of 50 putting strokes executed in sets of five. Both face angle and stroke path were altered from approximately $-5°$ to $5°$ in $1°$ increments. These ranges reflect extreme values for a golfer's putting stroke (Karlsen et al., 2008). Within each set of five putts, putter head speed was systematically increased to produce putts that rolled approximately 1 m on the first stroke and 6 m on the fifth stroke.

Validity: putter speed and impact spot. Unlike face angle and stroke path, which were precisely known from the set-up of the robot and lasers, the specific magnitude of putter head speed generated by the robot, although highly repeatable, required measurement by another device (i.e. high-speed camera). As such, using a robot for the putter head speed validity test provided no advantage. Furthermore, since the TOMI® system is used primarily to collect data on human golfers, the use of a human golfer improved the study's external validity. Putter speed and impact spot were varied systematically, by a live golfer, over

50 putts collected in sets of five. Within each set of five, the golfer attempted to hit each putt with the same putter speed. The first putt in each set was hit off the heel, the second between the heel and the centre, the third at the centre, the fourth between the centre and the toe, and the fifth off the toe. Each putt was captured using the high-speed camera, which was positioned 1.5 m above the putting surface such that the axis of the camera lens was perpendicular to the surface and directed through the ''sweet spot'' indicator on the top of the putter head. The field of view was 40 cm along the X-axis $\times$ 30 cm along the Z-axis (Figure 1a) and the resolution was 440×330 pixels. Each stroke was captured at 250 Hz with a shutter speed of 1/10,000 and the field of view was illuminated with two 500-W halogen bulbs. The ''sweet spot'' indicator on the top of the putter head was manually digitized using Maxtraq® (Innovision Systems, Inc., Columbiaville, MI) software. The point's coordinates at address (in the calibrated position) as well as through the impact area were collected for each stroke. Impact spot was calculated as the displacement of the centre of the putter head from address to impact along the Z-axis. Putter speed was calculated by applying the central difference method to putter head displacement along the X-axis.

Reliability of TOMI® and the high-speed camera. While a live golfer was appropriate for assessing the validity of the TOMI® system relative to the high-speed camera, a live golfer possesses too much variability for a test–retest type of reliability assessment. Therefore, trials were executed with the putting robot for determining the reliability of both the TOMI® and high-speed camera measurement methods. Two identical strokes were executed at each of 25 varying combinations of the impact variables.

Statistics

The reliability of the TOMI® and high-speed camera measurement methods were assessed using Bland and Altman's 95% limits of agreement as described by Atkinson and Nevill (1998). A paired *t*-test was used to assess the hypothesis of zero bias for each reliability measure. Heteroscedasticity of the differences between the test and retest scores was assessed using Pearson's *r* and the associated test for significance. Normality of the differences between the test and retest was assessed using the Shapiro-Wilk test. If meaningful heteroscedasticity was suspected or the data did not follow normality, then a natural logarithmic transformation of the data was performed before calculating the bias and limits of agreement (Enoksen, Tonnessen, & Shalfawi, 2009). The authors believe that the reliability of the

laser–grid system for indicating the true face angle and stroke path does not warrant evaluation. The validity of the TOMI® system, with respect to the laboratory measurements (laser–grid system and high-speed camera), was assessed using the method of comparison described by Altman and Bland (1983) and Bland and Altman (1986). The same statistics for bias, heteroscedasticity, and normality explained for reliability were also applied to the validity measures. In addition, 95% confidence intervals were calculated for the bias as well as the upper and lower estimate for each limit of agreement for the validity measures. The software package SPSS (Statistical Package for Social Sciences 15.0, SPSS Inc., Chicago, IL) was used for all statistical calculations.

To determine whether the TOMI® measurement system is of practical use in a research setting, the analytical goals were set based on the effect the estimated maximum measurement error would have on the success of an actual 4-m putt. Professional golfers have a 25% success rate from this distance, while the average amateur (20 $\pm$ 5 handicap) has a success rate of less than 10% (Pelz & Frank, 2000). This suggests that the success of a 4-m putt is sensitive to the typical variations in a golfer's putting stroke. If a golfer altered their putting stroke such that their success rate meaningfully changed from 4 m, then a valid and reliable stroke measurement method should be sensitive to these changes. Ninety-five percent confidence intervals were determined for both the upper and lower 95% limits of agreement for each of the four deterministic impact variables. The putting robot was then manipulated to execute 10 putts, from 4 m, at the most extreme value as indicated by the confidence intervals. The extreme values for each of the four impact variables were assessed separately. If the TOMI® measurement

system is valid and reliable, incorporating these errors into an actual putting stroke should result in no change in the success rate.

Results

Reliability

Test–retest reliability did not show any meaningful or statistically significant bias with either the TOMI® measurement system (Table I) or the high-speed camera measurement system (Table II). Examination of the histograms of the difference for each reliability measure as well as the Shapiro-Wilk tests indicated that all data sets followed a normal distribution. Systematic variation is presented as bias and the random variation as 95% limits of agreement. To be more explicit, consider the reliability of TOMI® in measuring face angle at impact (Table I). It can be said that for a golfer executing two identical putting strokes, there is a 95% probability that the measured difference in face angle at impact will lie between –0.22° and 0.20°.

Validity

The validity of the TOMI® measurement system for measuring face angle and stroke path was evaluated against the laser–grid system. The TOMI® measurement system did not show any meaningful or statistically significant bias relative to the laboratory measurements as indicated by the paired *t*-test *P*-values (Table III). The 95% limits of agreement for face angle indicate that the TOMI® system may be $-0.17°$ below or $0.21°$ above the laboratory measurement (Figure 3). Relative to face angle, the TOMI® method showed more discrepancy in

Table I. Reliability measures for the TOMI® measurement system ($n = 25$ pairs).

	Test	Retest	Paired *t*-test *P*-value	Bias	95% limits of agreement	Heteroscedasticity Pearson's *r*	*P*-value
Face angle (°)	0.03 $\pm$ 2.03	0.02 $\pm$ 2.03	0.49	-0.01	$\pm$ 0.21	0.01	0.95
Stroke path (°)	0.28 $\pm$ 2.16	0.26 $\pm$ 2.14	0.72	-0.02	$\pm$ 0.70	-0.15	0.41
Putter Speed (cm · s^{-1})	85.45 $\pm$ 19.94	85.40 $\pm$ 19.96	0.72	-0.05	$\pm$ 1.43	0.14	0.50
Impact spot (cm)	0.00 $\pm$ 0.30	0.00 $\pm$ 0.29	0.60	-0.01	$\pm$ 0.13	0.23	0.27

Table II. Reliability measures for the high-speed camera measurement system ($n = 25$ pairs).

	Test	Retest	Paired *t*-test *P*-value	Bias	95% limits of agreement	Heteroscedasticity Pearson's *r*	*P*-value
Putter speed (cm · s^{-1})	83.38 $\pm$ 25.5	83.33 $\pm$ 25.81	0.80	-0.05	$\pm$ 1.80	-0.17	0.47
Impact spot (cm)	0.33 $\pm$ 2.05	0.33 $\pm$ 2.06	0.90	0.00	$\pm$ 0.05	-0.02	0.95

Table III. Validity assessment of the TOMI® system relative to the laboratory measurements ($n = 50$ pairs).

	Laboratory	TOMI®	Paired t-test P-value	Bias	95% limits of agreement	95% confidence intervals		
						Bias	Lower	Upper
Face angle (°)	-0.09 ± 2.59	-0.07 ± 2.60	0.26	0.02	± 0.19	-0.01 to 0.04	-0.22 to -0.13	0.16 to 0.25
Stroke path (°)	0.36 ± 2.54	0.33 ± 2.72	0.74	-0.03	± 1.15	-0.19 to 0.14	-1.46 to -0.89	0.83 to 1.41
Putter speed (cm · s^{-1})	78.32 ± 18.51	78.52 ± 18.01	0.46	0.20	± 3.68	-0.33 to 0.73	-4.41 to -2.56	2.96 to 4.81
Impact spot (cm)	0.02 ± 1.48	0.01 ± 1.47	0.64	-0.01	± 0.33	-0.06 to 0.04	-0.43 to -0.26	0.24 to 0.41
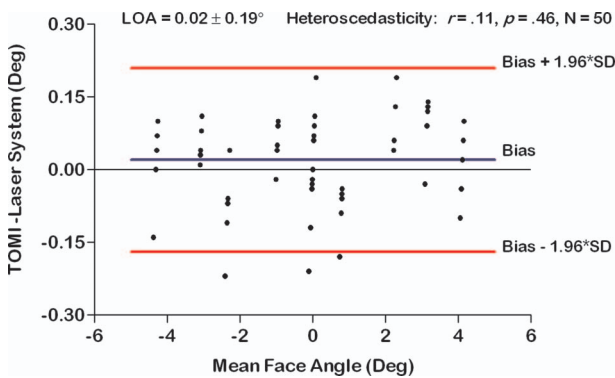
Figure 3. Bland-Altman plot for face angle showing the difference between the TOMI® and laboratory measurement plotted against the mean of the two measurements.
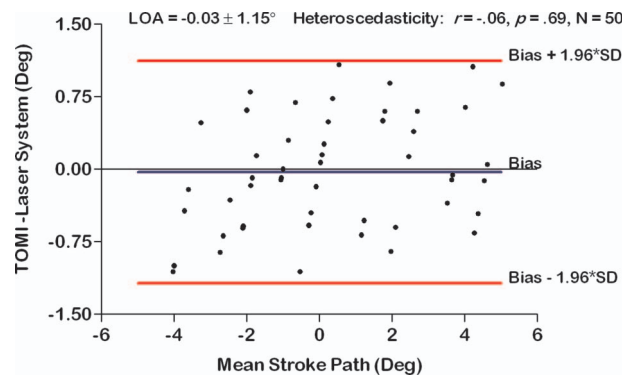
Figure 4. Bland-Altman plot for stroke path showing the difference between the TOMI® and laboratory measurement plotted against the mean of the two measurements.

measuring stroke path as the TOMI® measurement may be −1.18° below or 1.12° above the laboratory measurement (Figure 4). The larger discrepancy in measuring stroke path may be related to our particular data-processing techniques in combination with the accuracy with which the TOMI® clip can be placed on the putter shaft (Figure 2). The TOMI® camera only ''sees'' the four LEDs on the TOMI® clip and not the putter head, while the laser–grid system has no relationship to the clip. The data analysis program assumed that a line drawn between the two LEDs that protrude from the sides of the putter shaft was parallel to the target line (Figure 2). Assuming a vertical putter shaft (for simplicity), if the clip was rotated about the longitudinal axis of the putter by + 1°, the theoretical target line created by the analysis program would be misaligned with the true target line (as indicated by the laser–grid system) by 1°. Given this scenario, if the putter head was swung with only velocity in the true target line direction at impact, the analysis program would erroneously report a stroke path of −1°. A misaligned clip will not affect face angle. Since the clip is fixed rigidly to the putter, any angle the putter moves through results in an identical angular displacement of the clip. For example, given the previous scenario, if the putter head rotated back to square at impact,

then the clip would have undergone no net angular displacement and face angle would be reported as zero by the TOMI® system regardless of the alignment of the clip on the shaft.

The Bland-Altman plot of putter speed indicates that the TOMI® system had a small positive bias (0.2 cm · s^{-1}) and that the measurement may be −3.48 cm · s^{-1} below or 3.88 cm · s^{-1} above the high-speed camera measurement (Figure 5). The Bland-Altman plot for impact spot shows that the TOMI® system had a small negative bias (−0.1 cm) and that the measurement may be −0.34 cm below or 0.32 cm above the high-speed camera measurement of impact spot (Figure 6).

Discussion

The main aim of this study was to assess the validity of the TOMI® device, coupled with standard 3D coordinate data-processing techniques, in measuring putting kinematics. Validity was assessed according to the 95% limits of agreement technique proposed by Altman and Bland (1983) and Bland and Altman (1986). The method provides an indication of how much the TOMI® system can be expected to differ from the laboratory system on any given putting stroke. The biases as well as the upper and lower 95%
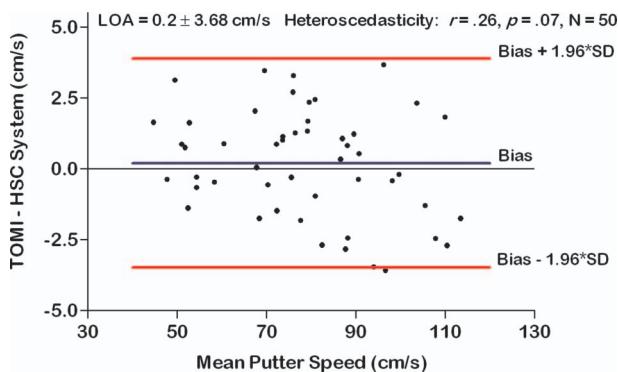
Figure 5. Bland-Altman plot for putter speed showing the difference between the TOMI® and laboratory measurement plotted against the mean of the two measurements.
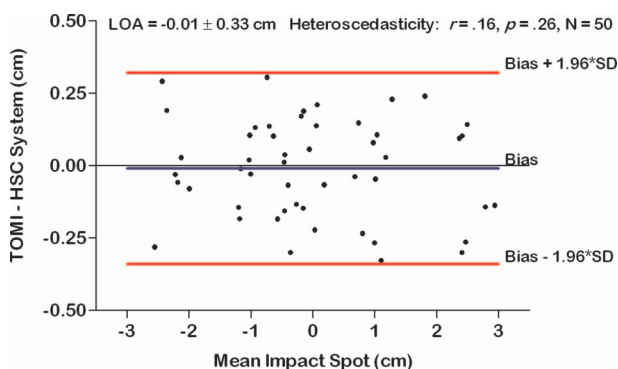

Figure 6. Bland-Altman plot for impact spot showing the difference between the TOMI® and laboratory measurement plotted against the mean of the two measurements.

limits are only estimates based on the sample of measurements. Therefore, confidence intervals for each bias and limit were calculated. The upper and lower bounds of the 95% confidence intervals essentially represent the largest error that could be expected for the TOMI® measurement system (Table III). From a statistical perspective, it would be conservative to use the bounds of the 95% confidence intervals when considering the analytical goals.

The analytical goals were based on the value of each impact parameter that would result in a missed 4-m putt. For a straight and flat 4-m putt, the optimal stroke would have zero face angle, zero stroke path, zero impact spot, and the optimum putter head speed. According to Pelz and Frank (2000), the optimum putter head speed is one that would roll the golf ball approximately 43 cm past the hole if it were smoothly covered. Since the radius of a golf hole is 5.4 cm, a putted golf ball that deviates from the centre of the hole by more than that amount will miss. For a straight and flat 4-m putt, a ball that is started 0.6° off the target line will be 1.2 cm inside the edge of the hole. A ball hit outside this line with the optimal speed will miss. Optimal speed can be

determined experimentally by executing a high number of putts, at the same speed, along a series of potentially successful target lines spanning the width of the hole. This can then be repeated for a range of systematically increasing ball speeds starting with the minimum speed required to reach the hole. The speed at which the most attempts are successful is the optimal speed. There is a trade-off: green irregularities have less influence on the path of a faster moving ball, but a faster moving ball has a greater chance of "lipping out". Therefore, it is possible for a ball to be struck at the optimal speed, within the width of the hole, and still miss.

From a Newtonian perspective, the ball's initial direction is a result of the forces exerted by the putter face during impact. If the putter face is square to the stroke path during impact, all of the force exerted on the ball will be in a direction perpendicular to the putter face. A force, due to friction between the putter face and ball, will arise when the putter face is not square to the stroke path during impact. Since the resultant force on the ball is, in part, dependent on the face angle and stroke path, it is convenient to estimate their individual effects on initial ball direction. While there probably is no set analytical equation for computing ball direction from putter head kinematics during impact, researchers have presented guidelines based on experimental data. Assuming contact at the centre of the putter face, these researchers have reported that stroke path accounts for 16–20% of initial ball direction, while face angle accounts for the remaining proportion (Cochran & Stobbs, 1968; Karlsen et al., 2008; Pelz & Frank, 2000; Werner & Greig, 2000).

Face angle has been reported to account for 83% of the initial direction of a putt (Pelz & Frank, 2000). Therefore, a face angle error greater than 0.7° is required to start the ball 0.6° offline. Results with our putting robot are in agreement; it was determined that a face angle of approximately 0.6° was necessary for the robot to start missing putts from 4 m. This is well above our maximum estimate of the limit of agreement (0.25°) (Table III). To confirm this, 10 putts were executed with a face angle of 0.25° and all putts were successful.

It has been reported that stroke path accounts for 17% of the initial direction of a putt (Karlsen et al., 2008; Pelz & Frank, 2000). Therefore, a stroke path error greater than 3.5° is required to start the ball 0.6° offline. This is well above our maximum estimate of the limit of agreement (–1.46°) (Table III). To confirm this, 10 putts were executed with a stroke path of –1.5° and all putts were successful.

Errors in putter head speed have an important effect on the success of a putt. For example, for a 15-handicap golfer, errors in speed were found to result in distance errors of 146 cm for 99.7% of 3-m putts,

while the corresponding errors due to impact spot variations were less than 8 cm (Werner & Greig, 2000). Pelz and Frank (2000) confirmed the importance of imparting the correct speed to the ball, stating that speed is four times more important than line. In our laboratory, a 4.8 cm $\cdot$ s^{-1} error in putter head speed would result in a ball displacement error of approximately 15 cm. The putting robot was calibrated to hit putts with a theoretically optimum putter head speed (143 cm $\cdot$ s^{-1}), which would have the putts finishing 43 cm past the hole if it were smoothly covered (Pelz & Frank, 2000). Therefore, a distance error of $\pm$ 15 cm should not affect the success of a 4-m putt. To confirm this, 10 putts were executed with a putter head speed of 138 cm $\cdot$ s^{-1} and 10 putts were executed with a putter head speed of 148 cm $\cdot$ s^{-1}; all putts were successful. It was determined that a decrease in putter head speed to 131 cm $\cdot$ s^{-1} or an increase to 158 cm $\cdot$ s^{-1} was necessary for the robot to start missing putts from 4 m.

Relative to the other three impact variables evaluated in this article, errors in horizontal impact spot have the least influence on the outcome of a putt. Based on the data provided by Nilsson and Karlsen (2006), a miss hit of 1 cm resulted in a 2% loss of roll length and a lateral error of less than 1% of roll length. Neither error would result in a missed putt from 4 m. Their data were collected using a "toe–heel weighted" putter similar to the model used in this study. According to Werner and Greig (2000), the scatter of stop points for a series of putts is negligible when the impact spots are within 0.8 cm of the face centre. This is well above our maximum estimate of the limit of agreement for impact spot (–0.43 cm) (Table III). Again, all 10 putts executed with this level of error were successful.

More focus has been placed on the validity measures since reliability is a necessary condition for a measurement method to be deemed valid. Karlsen et al. (2008) tested the ability of the SAM PuttLab® to reliably measure face angle at impact using a pendulum putting device. They reported the reliability of the SAM PuttLab® in measuring face angle by calculating standard deviations of 0.09° and 0.10° for two sets of 20 identical putts. When this standard deviation method is applied to our data, the result is a face angle reliability measure of 0.06°. Thus it would appear that the TOMI® measurement method assessed here is of the same level of reliability as other methods used in recently published putting studies.

Conclusions

The TOMI® device, when used in conjunction with standard 3D coordinate data-processing techniques, was found to be a valid and reliable method for measuring face angle, stroke path, putter speed, and impact spot, at the moment of ball contact. These findings are applicable for putts between 1 and 6 m in length. The validity of the TOMI® measurement system was quantified using the 95% limits of agreement method for each aforementioned variable. The practical significance of each validity score was assessed by incorporating the maximum estimated measurement error into the stroke of a putting robot for 10 consecutive putts. All putts were executed from a distance of 4 m on a straight and flat synthetic putting surface. Since all putts were successful, the measurement error for each variable was deemed to be negligible for the purposes of measuring putting stroke kinematics.

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