Sample Literature Reviews

The **Introduction** sections of the following journal articles will serve as a guide for writing your literature review. The Introduction section of a journal article is typically a condensed version of a literature review that contains only those bits of information, and arguments, which are critical to justifying the purpose of the study. That being said, the following Introductions contain the essential elements of a good literature review.

1. General introduction paragraph to the topic

2. Paragraphs organized by separate ideas
   a. Some paragraphs simply describe pertinent findings of previous research. Specific quantitative findings of previous studies (e.g., exact % of fat lost, jump height in centimeters, weight lifted in kilograms) should be included where possible.
   b. Some paragraphs critically analyze shortcomings of previous research. These criticisms set-up justification for the current study.
   c. Some paragraphs ‘connect the dots’ formed by information in previous paragraphs so the logic behind the justification of the study is explicitly spelled-out for the reader.

3. Carefully worded transitions between paragraphs that seem logical

4. A concluding paragraph which clearly states the purpose(s) of the study. The contents of this paragraph should be obvious to the reader if the Introduction is written correctly.

Sports Eng (2009) 11:165–175
DOI 10.1007/s12283-009-0020-9

ORIGINAL ARTICLE

A three-dimensional forward dynamics model of the golf swing

Sasho James MacKenzie · Eric J. Sprigings

Abstract Previously, forward dynamic models of the golf swing have been planar, two-dimensional (2D) representations. Research on live golfers has consistently demonstrated that the downswing is not planar. This paper introduces and evaluates the validity of a 3D six-segment forward dynamics model of a golfer. The model incorporates a flexible club shaft and a variable swing plane. A genetic algorithm was developed to optimise the coordination of the model's mathematically represented muscles (torque generators) in order to maximise clubhead speed at impact. The kinematic and kinetic results confirmed previous findings on the proximal to distal sequencing of joints and the muscles powering those joints. The validity of the mathematical model was supported through comparisons of the model's swing kinematics and kinetics with those of a live golfer.

1 Introduction

Over the past 40 years, the golf swing has been analysed using kinematic [1], inverse dynamic [2] and forward dynamic [3] methods. The appropriateness of the method depends on the research question being addressed. For example, a kinematic analysis provides a description of the motion and is suitable for describing the orientation of a golfer's swing plane [1]. An inverse dynamic method estimates the underlying kinetics for a particular swing and, as one example, is appropriate for estimating the torque acting at the wrist during the downswing [4]. Forward dynamic methods widen the scope of possible research questions by permitting "what if" questions to be investigated [5]. Provided the forward dynamic model is valid, a researcher can investigate such things as the influence, on clubhead speed, of an optimally delayed wrist torque [6]. Regardless of the method, most researchers have made simplifying assumptions to make the analysis tenable. The key is to ensure that the simplification is inconsequential to the particular question being addressed.

A recurrent simplification in the golf swing literature has been the assumption that the downswing can be represented as a movement occurring in a single constant plane [3, 6–16]. However, there is research which suggests the downswing is not planar. Vaughan [4] and Neal and Wilson [2] performed three-dimensional (3D) inverse dynamic analyses of the golf swing which described the kinetics at the golfer's wrist; however, perhaps more relevant to future golf swing modelling research, both studies concluded that the shaft did not move in a constant plane. Vaughan [4] stated that the plane was nearly constant during the last half of the downswing but variable during the first. Conversely, Neal and Wilson [2] suggested the opposite and that the club moved in one plane only for the first half of the downswing. Performing a kinematic analysis, Coleman and Rankin [1] conducted a study which measured the 'left-arm plane' of the golfer's motions and the position of the club relative to that plane. They concluded that the golfer's motions in the downswing were not planar, and the motions of the club were not coincident with the plane established by the motion of the golfer's lead arm and trunk. Measuring an impressive number of 84 golfers, Nesbit [17] reported that the downswing does not take place in a fixed plane. Based on these findings, it

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appears that the club and lead arm are not coplanar and that the plane they move in throughout the downswing is not constant.

While being forward dynamic in nature, Nesbit's model [17] differed from early forward models [3, 9, 14] in that the model was driven by the kinematic patterns of a real golfer. Nesbit captured the 3D kinematics of a swing, fitted each joint angular displacement series with a cubic spline and used these splines to drive the movement of the model. The study provided a thorough kinematic and kinetic description of the swings of 84 separate golfers. While the forward model served as verification to Nesbit's data collection and analysis procedure, it appears his results could have been generated with an inverse dynamics model alone. Recently, Kenny et al. [18] conducted a study, with a methodology similar to that of Nesbit, to investigate the transfer of kinetic energy through the golfer. Kenny et al.'s methodology included an extra step which involved using the captured 3D kinematic data to "train" muscle joint torques in a golfer model. The joint torques were then employed to drive the forward dynamic model. A major finding from their analysis, of a single category 1 golfer, was that the kinetic energy of the arms peaked first suggesting that the optimal coordination of sequencing was not proximal to distal. Of note is their use of the term optimal. There was no manipulation of the model input variables (computed joint torques) to improve some aspect of the model's output behaviour (clubhead speed). Rather, it must be inferred that, they assumed that their test golfer had an optimal swing. While this is possible, there is no way to confirm it. Ideally, they would have manipulated the activation patterns of the model's "trained" muscles, using actual optimisation techniques, to maximise clubhead speed. Following this optimisation, an investigation into the kinetic energy sequencing could have been conducted. Showing that their model closely matched the swing of a live golfer demonstrates the validity of the model, but it does not mean that the model has optimal swing kinematics. If the input kinetics driving a forward model were determined from a specific kinematic pattern, then would the forward model not be expected to reproduce the same kinematics? Similar to the findings of Nesbit [17], Kenny et al.'s question of energy sequencing could have been answered using the initially captured kinematic data without employing the forward-driven simulation. It is not clear if their model can be optimised by manipulating the input kinetics in the manner described by earlier researchers employing forward dynamics and optimisation [19–21]. Although not employed for this purpose, perhaps the major value of Kenny et al.'s model lies in its ability to demonstrate the precise patterns of activation of individual muscles.

While inverse dynamic studies, and the limited forward dynamic studies just described, have advanced the understanding of the golf swing, they are primarily descriptive in nature and as such are restricted in their capacity to test theories. For example, they are not well suited to answer questions such as, "How would clubhead speed change if the golfer exerted no wrist torque during the downswing?" However, with the appropriate model, it is possible to alter the representative muscle activity patterns and answer questions such as the one posed above. Further, it is possible to incorporate an optimisation scheme that conducts a search for the particular muscle activity pattern that yields the 'best' kinematics. While not prone to experimental error, forward dynamic models are susceptible to structural validity concerns. That is, how well does the model physically represent the actual system?

It seems unlikely that a 2D model could provide a valid means for investigating the behaviour of the golf club shaft. This premise is based on the fact that, during the downswing, the club rotates approximately 90° about the longitudinal axis of the lead arm. Despite this fact, the role of shaft stiffness in the golf swing has previously been investigated using 2D forward dynamic models [11, 15, 22]. Perhaps the most-cited study on the role of shaft stiffness is that of Milne and Davis [11], which employed a similar 2D model as that of Budney and Bellow [23], but also incorporated a mathematical representation of shaft bending so as to evaluate the role of shaft stiffness. Milne and Davis concluded that shaft flexibility does not play an important dynamic role in the golf swing. However, there is an important validity concern with the mathematical model developed by Milne and Davis that stems from their attempt to model the 3D nature of shaft dynamics. Milne and Davis realised that an essential requirement of a simulation of shaft bending was that it be 3D. They stated that the main reason for this is that the centre of mass of the clubhead does not lie on the projected line of the shaft. Although presented in a vague fashion, it appears that clubhead rotation about the longitudinal axis of the lead arm was incorporated into their simulation in the following way. From live golfer tests, the distance of the centre of mass of the clubhead from the projected shaft line in the swing plane was determined as a function of the angular position of the shaft. The centre of mass of the clubhead was constrained in their 2D simulations to change its position relative to the shaft as a function of wrist angle. Basically, Milne and Davis developed a 2D forward dynamics model in an attempt to resolve a 3D dynamics problem. The applied torques in the system acted in a single plane, and the inertial properties of the system's segments were only expressed for motion in a single plane. According to classical dynamics, the change in motion of a body does not occur without the application of a force or torque. In reality, some mechanism, perhaps a muscular torque, must cause the clubhead to rotate about the longitudinal axis of the lead arm in the plane of the swing. Such a mechanism would also have an effect on shaft bending. This mechanism was not represented in the model employed by Milne and Davis and therefore its effect on shaft bending cannot be evaluated.

Based on our review of literature, the golf swing is fundamentally 3D, not planar. Further, any model that attempts to investigate the underlying kinetics of the swing, and the resulting club shaft dynamics, should represent the 3D motion of the golfer and club.

The main purpose of this paper was to develop a 3D forward dynamics model of the golf swing to satisfy this condition. The model's validity was tested by comparing its kinematic and kinetic output to the swing of a live golfer. Following validation, the model was optimised to maximise clubhead speed at impact. The general kinematic and kinetic profiles are reported and compared to findings in the literature.

2 Methods

2.1 Live golfer data collection

A category 1 male golfer (1.83 m, 80 kg and 3 handicap) was used to test the validity of the model. Prior to participating, the participant signed a document of informed consent. The research was approved by the University of Saskatchewan Research Ethics Board. The participant completed a warm-up consisting of ten swings with a driver in which a golf ball was hit into a net from a tee in a laboratory setting. The driver used had a total mass of 310 g and was fitted with a 'regular' shaft. According to the USGA Rules of Golf measurement convention, the driver was 116.5 cm in length [24]. The participant was instructed to swing consistently from shot to shot and to swing as they normally would on the golf course. Following the warm-up, the participant completed six 'well-executed' drives which were captured using a high-speed digital video camera (MotionScope PCI 1000) at a sampling rate of 500 fps and a shutter speed of 1/1,500 s. If the participant felt a particular drive was not well executed, then that trial was repeated. To orient the axis of the lens in a position that was approximately perpendicular to the swing plane, the camera was placed 5.1 m away horizontally and 5.5 m above ground level. Access to a single high-speed camera limited the kinematic data collection to only two dimensions. A high frame rate is necessary to capture the high-speed movements of the downswing. The use of a multiple camera kinematic data collection system would have been preferred.

The video of each swing was analysed using the motion analysis software HU-M-AN^{TM}. Displacement data throughout the swing were generated by manually digitising points on the golfer's right shoulder (lateral edge of acromion), left shoulder (lateral edge of acromion), left wrist (styloid process of the radius) and clubhead (at the hosel). These four points defined a three-segment model (torso, lead arm and club) which could be analysed in HU-M-AN^{TM}. This collection model was chosen to permit comparison of the live golfer results to that of the forward dynamics model described later. The raw coordinate data were low-pass filtered using HU-M-AN's built-in fourth-order recursive Butterworth filter. Cut-off frequencies, ranging from 5 to 19 Hz, were individually selected for each of the X and Y coordinate data sets for each point based on their residual plots [5]. Following smoothing, the absolute angular displacements of the torso, lead arm and club were calculated. The swing that resulted in the highest clubhead speed at impact was selected to test the validity of the model. The participant demonstrated a repeatable swing with an average clubhead speed of 39.9 ± 0.5 m/s.

2.2 Model geometry, rotations and constraints

Kane's commercial software package, Autolev^{TM}, was used to generate the 3D equations for a six-segment (torso, arm and four club segments) mathematical model of a golfer (Figs. 1, 2). Such a model can represent the four primary motions executed in the downswing: torso rotation, horizontal abduction at the shoulder, ulnar deviation at the wrist and longitudinal rotation about the lead arm

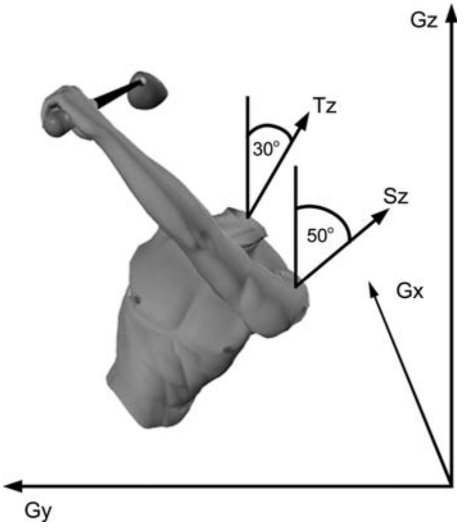

Fig. 1 The initial configuration for the 3D, six-segment model used to simulate the downswing. The global inertial reference frame, G, formed the basis for the model's motion with G_x directed towards the target. The *Torso* was constrained to rotate about axis T_z, while the *Shoulder* was constrained to have rotation about the S_z axis

Sports Eng (2009) 12:13–19
DOI 10.1007/s12283-009-0028-1

ORIGINAL ARTICLE

Understanding the role of shaft stiffness in the golf swing

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Abstract Theoretically, shaft stiffness can alter shot distance by increasing clubhead speed or altering clubhead orientation at impact. A 3D forward dynamics model of a golfer and flexible club simulated the downswing. A genetic algorithm optimized the coordination of the model's muscles (four torque generators) to maximize clubhead speed. The maximum torque output and maximum rate of torque development from the torque generators were varied to simulate the swing of golfers that generate different clubhead speeds. Four shafts of varying stiffness (flexible, regular, stiff, and completely rigid) were entered into these simulations to examine the role that shaft flexibility had on clubhead speed and orientation at impact. Shaft stiffness was found to have a meaningful effect only on clubhead orientation (dynamic loft and dynamic close) at impact. There was no evidence to support the premise that matching the stiffness properties of the shaft with the golfer would improve clubhead speed.

Keywords Golf · Shaft flexibility · Computer simulation · Optimization · Three-dimensional · Forward dynamics · Genetic algorithm

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1 Introduction

Over the years, the golf club has gone through many modifications to improve performance. In response to the evolution of design changes, the governing bodies (United States Golf Association and The R&A) have introduced regulations on golf equipment aimed at protecting the best interests of the game [1]. Golf club manufacturers are now focusing on new strategies to attract consumers such as customizing the stiffness of a golf club's shaft to an individual's swing. The stiffness of a shaft can, in theory, exert its influence on the resulting ball flight in two ways. The first involves the shaft's ability to store and subsequently release strain energy which could result in an increase in clubhead speed. The second is by altering the orientation of the clubhead relative to the ball at impact. The orientation of the clubhead will affect the distance the ball travels by changing the launch angle relative to the horizontal, the direction of ball flight, and the spin rate of the ball.

Prior to impact with the ball, the shaft can be measured bending about three orthogonal axes fixed to the grip end of the club. Deflection along the *Y* axis represents lead/lag motion (Fig. 1a), while deflection along the *X* axis represents toe-up/toe-down motion (Fig. 1b). Twisting about the longitudinal, *Z,* axis of the shaft can also occur. Compared to the magnitude of deflection about the other axes, twisting about the longitudinal axis has a negligible influence on both the orientation of the clubhead and its velocity at impact, and therefore, will not be considered in this paper [2]. Butler and Winfield [2] measured peak deflection values in the lag direction as large as 7 cm, and peak deflections in the toe-up direction greater than 15 cm. In their study, three golfers swinging the same club at 46 m/s, produced toe-down deflections at impact that ranged from approximately 0.5–5 cm, while lead deflections at impact ranged from approximately 0.3–4 cm. Mather and Cooper [3] found that, for a 'good player' swinging a driver, both the lead and toe-down deflections at impact can be as large as 5 cm. Horwood [4] determined that, for one golfer swinging a stiff flex shaft with a clubhead speed of 42.5 m/s at impact, the clubhead moved through 12.7 cm from its maximum lagging position into its maximum leading position. For a group of golfers with an average clubhead speed of approximately 46 m/s, Nesbit [5] measured an average lead deflection of approximately 6 cm at impact. Perhaps the most cited study regarding the role of the shaft in the golf swing is that of Milne and Davis [6]. A graph of their computer simulation values showed 'in-swing-plane' deflection values exceeding 10 cm. Since Milne and Davis employed a 2D model, it is assumed that 'in-swing-plane' refers to a blend of lead/lag and toe-up/down deflection. Based on the findings in the literature, it appears that the shaft does bend considerably during the swing.

Researchers have attempted to quantify the effect of shaft bending on clubhead speed. Nesbit [5] stated that shaft flexibility plays an important part in generating clubhead velocity through correct timing of the recoil of the shaft. The speed generated from the recoil of the shaft near impact is referred to as kick velocity [2]. Mathematically, kick velocity is the derivative of lead/lag deflection with respect to time. Butler and Winfield [2] calculated kick velocities at impact that ranged from 2.27 to 2.48 m/s. Horwood [4] made similar findings and determined that the maximum kick velocity was 5% (2.01 m/s) of the total clubhead speed (42.5 m/s). Contrary to these findings, Milne and Davis [6] concluded that shaft flexibility does not play an important dynamic role in the golf swing. It is unclear from their published work how this conclusion was reached. As stated previously, their results demonstrated large clubhead deflections during the downswing ($\sim$10 cm), which implies the storage of strain energy and the possibility of kick velocity adding to the overall clubhead speed. However, there was no mention of kick velocity in the paper or how shaft bending during the swing affects clubhead speed. MacKenzie [7] provided a critique of the simulation methods used by Milne and Davis [6], which called into question their two-dimensional model's ability to evaluate shaft flexibility. Recently, Worobets and Stefanyshyn [8] experimentally examined the influence of shaft stiffness on clubhead speed by having 21 golfers execute ten swings with each of five shafts of varying stiffness. For the majority of the golfers (12/21), shaft stiffness was reported to have no effect on clubhead speed; however, shaft stiffness did have an effect for nine of the participants. The fact that all of their tested golfers demonstrated "remarkable swing consistency" contributed to the researchers' inability to explain the ambiguous results. Without information on golfer hand speed, it cannot be definitively determined whether changes in clubhead speed were a result of altered shaft dynamics or modified golfer kinematics. The exact methods of filtering and interpolating the kinematic data to determine clubhead speed at impact were not reported. These procedures are not trivial as the clubhead would experience high frequency movement (due to ball impact) at the precise time when the swings' representative clubhead speeds were measured.

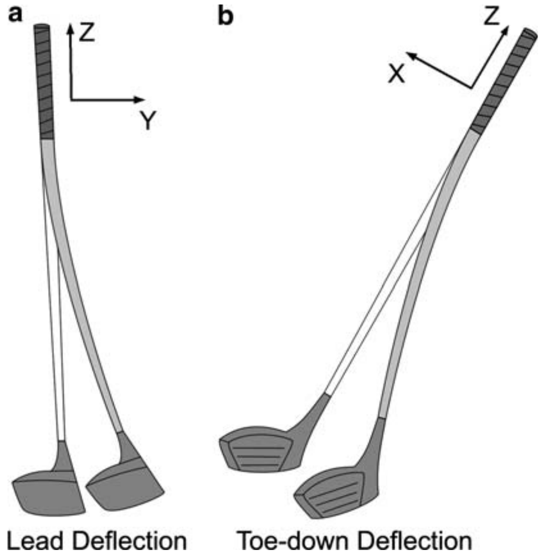

Fig. 1 The modeled shafts were capable of deflecting about two axes. **a** Deflection along the *Y* axis represents lead/lag motion. **b** Deflection along the *X* axis represents toe-up/toe-down motion

Although it is generally accepted that the orientation of the clubhead relative to the ball is altered by the shaft bending near impact, few studies have attempted to quantify the effects. Mather and Cooper [3] stated that depending on the geometry of the shaft, a lead deflection of 5 cm can result in a 5° increase in the loft of the club. They refer to this added loft as dynamic loft (Fig. 2a). Horwood [4] explained that increasing the lead deflection at impact would increase the dynamic loft at impact and result in a higher ball trajectory. Dynamic close also occurs as a result of clubhead deflection and is a close in the face of the clubhead relative to the intended clubhead direction (Fig. 2b). Although not explicitly reported by any of the previously mentioned researchers, bending in the toe-up/toe-down direction may also alter ball flight.

The purpose of this paper was to gain an understanding of the role that shaft stiffness plays during the golf swing. This was accomplished through the use of mathematical modeling and optimized computer simulation techniques.

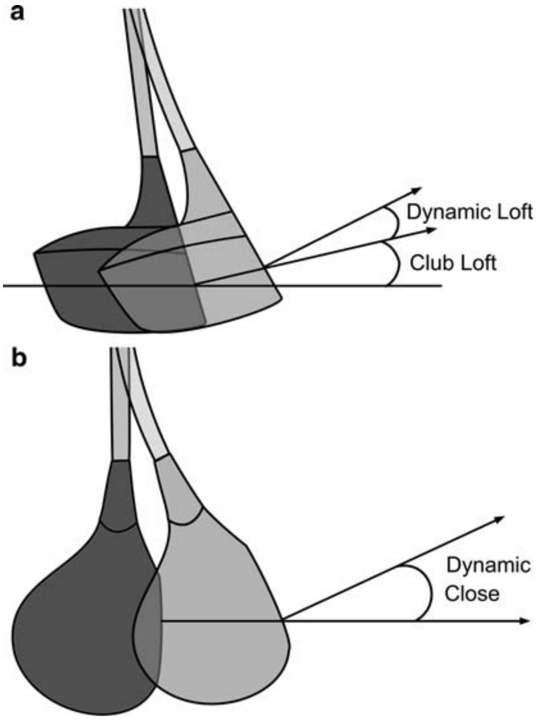

Fig. 2 **a** Dynamic loft is the change in nominal club loft that results from clubhead deflection. **b** Dynamic close also occurs as a result of clubhead deflection and is a close in the face of the clubhead relative to the intended clubhead direction

2 Methods

2.1 Model description

A representative mathematical model of a golfer was constructed using a six-segment (torso, arm, and four club segments), 3D, linked system (Fig. 3). The golfer portion of the model had four degrees of freedom. The model was capable of torso rotation, horizontal abduction at the shoulder, external rotation at the shoulder, and ulnar deviation at the wrist. Four muscular torque generators, which adhered to the force–velocity and activation rate properties of human muscle, were incorporated to add energy to the system. The four segments of the modeled club were connected in series by rotational spring-damper elements (Fig. 3). The hand and most proximal club segment were combined to represent a single segment, *Club_Proximal* [5]. The shafts were capable of deflecting about two axes (Fig. 1). Further details on model development and parameters have previously been presented [9].

Three versions of the same base model were used in this study. They differed only with regards to the constraint parameters governing the maximum torque output from the four torque generators. This allowed the role of shaft flexibility to be evaluated for golfers that generate three different levels of clubhead speed (i.e. Golfer-Slow ~35 m/s, Golfer-Medium ~43 m/s, and Golfer-Fast ~50 m/s). These clubhead speed values represent the minimum, average, and maximum clubhead speeds measured by Brown et al. [10] on a group of 40 male golfers (age 20–59; handicap 14 ± 8).

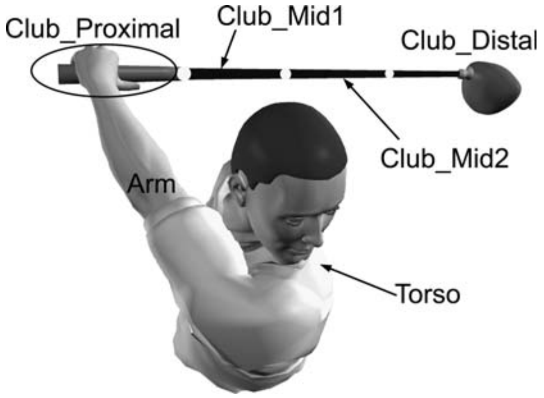

Fig. 3 The initial configuration for the 3D, six-segment model used to simulate the downswing. Note that the most proximal club segment was comprised of both the golfer's hand and grip of the club

2.2 Determining shaft stiffness and damping parameters

Separate stiffness constants for each of the three interconnecting springs were experimentally determined so that three shafts of varying stiffness could be employed in the model. To achieve this, three identical metal drivers were fitted with shafts of different stiffness (flexible, regular, and stiff) by a club professional with 30 years of experience. Each constructed club was measured to have a D1 swingweight. Once constructed, each club was rigidly secured in a vise so that the first 30 cm of the grip end was completely rigid (Fig. 4). This simulated the modeled club which was completely rigid for the first 30 cm. Markers were placed on the shaft so as to identify the segments defined by the mathematical club model. A 1 kg mass was suspended

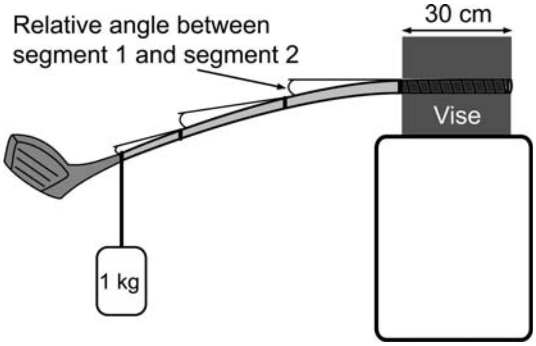

Fig. 4 Experimental set-up for determining shaft stiffness