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An ecological-dynamical approach to golf science: implications for swing biomechanics, club design and customisation, and coaching practice

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ABSTRACT

It has previously been argued that science has only made a limited contribution to the sport of golf, particularly the human element. This lack of impact could, in part, be attributed to the absence of an appropriate theoretical framework in most empirical investigations of the golf swing. This position paper outlines an ecological-dynamical approach to golf science that is better able to capture the interactions among the many structural parts of a golfer, and the relations between a golfer, his or her equipment, and his or her surrounding environment than other theoretical approaches have hitherto. It is proposed that the conjoining of principles and concepts of ecological psychology and dynamical systems theory could make a significant contribution to the enhancement of knowledge and understanding of swing biomechanics, club design and customisation, and coaching practice. This approach could also provide a platform on which to integrate the various subdisciplines of sport and human movement science to gain a more holistic understanding of golf performance.

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Introduction

Over the years, golf science has been criticised for not having the impact on the sport that perhaps it should have had or is commonly believed to have had. For example, Neal et al. (2001) observed:

> *As scientists, we would like to believe that systematic analysis of golfers and their swings has led to changes in practice and performance over the last 25 years. In truth, golf-interested scientists have served in an advisory capacity of providing explanations as to why a particular change actually worked, or whether a product is likely to provide the promised benefits. However, after examining the scientific literature, it appears as though golfers and their coaches, as well as equipment manufacturers appear to be the people who have led the revolution of change in golf. This is not a criticism but simply a statement of what has transpired to date.* (pp. 189–190)

Additionally, Zumerchik (2002) commented:

> *Science has actually contributed very little to the discoveries made in golf: It usually only confirms what has been proven through the endless trial and error experimentation that takes place every day on golf courses throughout the world. The history of innovations in golf often*

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> *goes something like this: An experiment is tried, results follow that show it works, and then only later, after the innovation has been widely adopted, is it proven to be scientifically sound. For instance, up until very recently the design of equipment, selection of materials, and evaluation of performance have been rather scientifically unsophisticated. Usually this haphazard analysis has been used primarily to confirm the efficacy of an existing direction of innovation or an improvement already advocated; rarely has scientific research alone resulted in a revolutionary discovery. The greatest contribution of science has been in the refinement of innovations after a scientific analysis has shown that it works and why . . .* (p. xv)

Although the volume of published golf-related scientific research has been steadily increasing since the publication of the seminal text by Cochran and Stobbs (1968), and has further expedited in the three decades following the inaugural World Scientific Congress of Golf held in St Andrews in 1990, it could be argued that many of the aforementioned observations are still applicable today.

One reason why science has only had a limited impact on the human element of the sport, in particular, is that there has been a lack of focus on the coordination and control of the golf swing and the internal and external factors that shape these behavioural patterns. Indeed, Martin (2008) argued that it is insufficient just to analyse how body segments rotate during the golf swing, how these rotations are timed with respect to one another, and how energy is transferred between body segments and to the club, although that would still represent substantial advancement, especially if applied at the individual level. Rather, he suggested that biomechanical analyses should be combined with theory and data from other subdisciplines of sport science, including sport physiology and sport psychology, to get a more complete understanding of the golf swing. This integrated approach, however, would necessitate an underpinning interdisciplinary theoretical framework, which has been absent from most empirical investigations of golf performance hitherto. The lack of an appropriate theoretical framework has also meant that many extant studies have failed to attend to substantive issues, such as variability and consistency of technique within and between golfers, in part, because they have been deemed to have limited theoretical relevance as any variability has been typically disregarded as noise or error (e.g., Glazier & Lamb, 2018; Glazier, 2011; Langdown et al., 2012).

In this position paper, an ecological-dynamical theoretical approach to golf science is outlined, which could make a significant contribution, *inter alia*, to the enhancement of knowledge and understanding of swing biomechanics, club design and customisation, and coaching practice. In the context of golf, the ecological-dynamical approach proposes that patterns of coordination and control defining the golf swing emerge from the confluence of interacting constraints via the formation and self-organisation of coordinative structures (Bernstein, 1967; Kelso, 1995; Kugler et al., 1980; Newell, 1986) and that perceptual information can be directly and unambiguously picked-up and used to tune or modulate these task-specific structural units (Fajen et al., 2009; Fitch et al., 1982; Gibson, 1966, 1979; Turvey, 1977). As will be discussed, the ecological-dynamical approach appears to be well-suited, not only to providing greater insights into interactions among parts of a golfer's body (e.g., pelvis-thorax coupling), but also relations between golfers and their surrounding environment, and, more importantly, between golfers and their golf clubs. This theoretical approach also provides a platform on which to integrate principles, concepts, methods, and data from the other subdisciplines of sport and human movement science (see Glazier, 2014, 2017), thereby enabling a more holistic understanding of golf performance to be gained, as identified as a research priority by Dillman and Lange (1994), Farrally et al. (2003), and Martin (2008). To begin, the task demands of hitting a golf shot are described and theoretical explanations about how a golfer may meet these requirements are considered before a unifying theoretical model of the golfer is outlined.

Hitting a golf shot: task description and theoretical explanations

The task of hitting a golf shot is a complex one. Despite the spatial and temporal certainty of striking a stationary golf ball at a stationary target, the golfer must ensure that the many interacting structural parts or degrees of freedom of his/her movement system (e.g., joints, muscles, motor units, neurons, etc.) are suitably organised to enable the golf club to be delivered to the ball with the appropriate force and club face orientation to produce the desired ball flight trajectory and shot outcome (Williams & Sih, 2002). The golfer must also contend with changeable environmental factors (e.g., atmospheric conditions, undulating terrain, etc.) of the golf course whilst concomitantly managing fluctuations in psychological (e.g., anxiety) and physiological (e.g., fatigue) states.

To date, most theoretical explanations of how golfers meet the requirements of hitting a golf shot have been based on principles and concepts from information processing theory derived from cognitive psychology and computational neuroscience (e.g., Marteniuk, 1976; R. A. Schmidt et al., 2018; Wolpert, 1997). From this perspective, the duration, magnitude, and relative timing of muscle activation defining the golf swing are prescribed by a motor program stored in the golfer's brain and controlled in open-loop fashion (e.g., Abernethy et al., 1990; Barclay & McIlroy, 1990; Jäncke et al., 2009; Neal et al., 1990). Over the years, however, the motor program concept, in particular, and the information processing approach, more generally, have come under intense criticism from sceptics who have targeted issues related to: the limited storage capacity of the long-term memory; the computational burden associated with the hierarchical control of a seemingly infinite number of independent degrees of freedom; the insensitivity to changes in internal and external conditions; and the problem of context-conditioned variability, to name but a few (Carello et al., 1984; Kelso, 1981; Turvey et al., 1982). Although the motor program concept has undergone substantial revision, most notably by R. A. Schmidt (1975, 2003), to make it more abstract and, therefore, more versatile, the explanatory power of information processing theory in the context of flexible and adaptive motor behaviour in dynamic performance environments typically found in sports like golf remains questionable (e.g., Davids et al., 1994, 2008; Handford et al., 1997).

An alternative theory, advocated in this paper, that has rarely been used to explain how the task requirements of hitting a golf shot are met (although see Knight, 2004, for an initial move in this direction), is the ecological-dynamical approach. This theoretical approach, which conjoins key principles and concepts from ecological psychology and dynamical systems theory, asserts that, rather than being explicitly prescribed by a motor program, patterns of coordination and control that characterise the golf swing emerge from ubiquitous processes of physical self-organisation (Kelso, 1995) and the confluence of interacting constraints (Newell, 1986) impinging on the golfer (see Glazier & Robins, 2013, for an overview of these constructs in the context of sports performance).

Constraints can be viewed as boundaries, limitations, or architectural design features that apply restrictions to movement. Following Newell (1986), constraints can be categorised as being either golfer-related (e.g., body mass and composition, anthropometric and inertial characteristics of body segments, strength and elasticity of skeletal muscle, etc.), environment-related (e.g., weather conditions, surface compliance, course topography, etc.), or task-related (e.g., shot distance, club properties, rules, etc.). In addition to placing physical restrictions on golfers, constraints can be informational in nature, providing metaphorical 'equations of constraints' that get 'written over' degrees of freedom of the golfer's movement system to form functional collectives known as coordinative structures (Saltzman, 1979; R. C. Schmidt & Fitzpatrick, 1996; Tuller et al., 1982). These equations of constraint specify the mutual dependencies among degrees of freedom, thereby simplifying the control problem. Once formed, degrees of freedom self-organise with other degrees of freedom comprising the same coordinative structure, and coordinative structures, which themselves can be considered as a single degree of freedom (Turvey et al., 1978) because of their self-similar (fractal) characteristics, self-organise with other coordinative structures to produce well-defined movement trajectories known as attractors. These attractors graphically represent the observable patterns of coordination and control that define the golf swing.

To understand more about how informational constraints shape patterns of coordination and control that define the golf swing—or, more specifically, how perceptual e.g., visual, haptic, auditory) information can be picked-up and used to tune or modulate coordinative structures—it is necessary to invoke principles and concepts from ecological psychology (Gibson, 1966, 1979). In contrast to information processing theory, which maintains that perceptual information about the surrounding environment is equivocal and impoverished and, therefore, requires embellishment by memorial processes, ecological psychology suggests that environmental information is rich and meaningful and can be directly and continuously picked-up from the environment with minimal cognitive intervention (Fajen et al., 2009; Gibson, 1966, 1979; Michaels & Carello 1981). The task of performing a golf shot requires the integration of multiple sources of sensory information, most notably visual information about the intended target, the golf ball, and the turf it is lying on, and haptic information about the position and orientation of body segments and the golf club throughout the duration of the swing. In the former, the surface of the ball and turf have different texture elements that reflect light to form a densely structured optic array at the golfer's eye (e.g., Lee, 1980). In the latter, the deformation of muscular and tendinous tissues of key body segments and joints continuously stimulates mechanoreceptor discharge (e.g., Turvey, 1996). In both instances, the structured energy distributions provide reliable patterns of information called *invariants* that can be directly perceived and used to tune coordinative structures (Fitch et al., 1982; Turvey, 1977). However, what opportunities for action or *affordances* these higher-order invariants offer depends on the action capabilities (e.g., strength, speed, mobility, etc.) of the golfer. Importantly, '*Affordances do not cause behaviour but constrain or control it*' (Gibson, 1982, p. 411). As will be discussed in the 'Club design and customisation' section, these theoretical concepts potentially offer a more principled basis for the custom fitting of golf clubs to individual golfers than other methods have hitherto.

A unifying theoretical model of the golfer

Recently, Glazier (2014) suggested that the constraints model proposed by Newell (1986) could provide the basis for a unifying theoretical model of the golfer and, by extension, golf science (see also Glazier, 2017, for further expansion of this approach). In the schematic shown in Figure 1, the shaded areas summarise how patterns of coordination and control, which ultimately determine impact conditions and shot outcome (assuming neutral environmental conditions), emerge from the confluence of interacting constraints via the formation and self-organisation of coordinative structures. The unshaded areas indicate where the various subdisciplines of sport and human movement science could be integrated to provide interdisciplinary insights and a more holistic understanding of golf performance.

In reverse order, working back from the shot outcome, the potential roles and contributions of the different subdisciplines identified in the unshaded areas of Figure 1 can be summarised as follows:

- Performance analytics can interpret shot outcome data obtained from databases such as ShotLink® to objectively identify variables and playing strategies that are associated with high-level golfing performance (e.g., Broadie, 2014; Broadie & Hurley, 2017; James, 2007, 2009).
- Sport technology can provide the apparatus for measuring and analysing impact conditions and ball flight. Launch monitors can provide extensive information about club (e.g., speed and path, attack and face angles, dynamic loft, etc.) and ball (e.g., speed, launch angle, spin rate, etc.) dynamics. Some of these devices, such as TrackMan® (TrackMan A/S, Denmark) and Foresight® (Foresight Sports, San Diego, CA), have previously undergone independent testing and have been shown to demonstrate adequate accuracy and validity for coaching and club fitting purposes (e.g., Leach et al., 2017). As will be discussed in the 'Coaching practice' section, the data provided by these devices can be used as a basis for directed search or

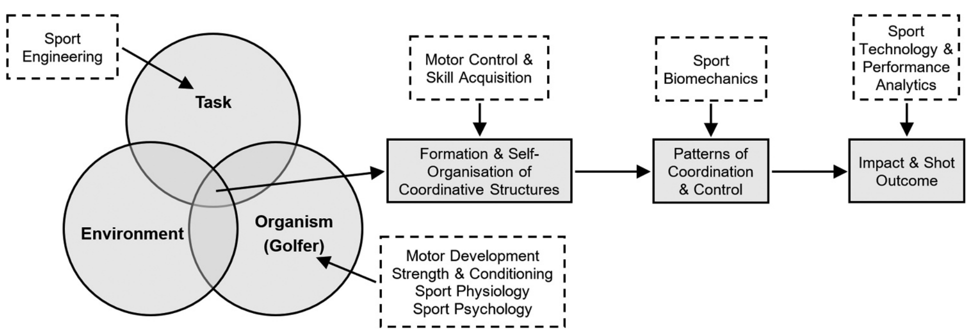

Figure 1. An adapted (drawn as a Venn diagram) and extended version of Newell (1986) model of constraints as applied to golf (adapted from Glazier, 2014).

guided discovery learning in which augmented information is used to channel, rather than specify, the patterns of coordination and control to be adopted (Glazier, 2010).

- Sport biomechanics can provide the methods and tools for measuring and analysing patterns of coordination and control that define the golf swing predominantly at the behavioural level of analysis (Glazier et al., 2003, 2006). As will be discussed in the 'Swing biomechanics' section, this type of analysis would represent a significant departure from the more conventional biomechanical paradigms that have featured previously in the golf science literature. The neuromuscular level of analysis is accessible but measurement tools and techniques for analysing the output of individual degrees of freedom, such as muscles or motor units, are inherently limited in a practical context (Glazier & Davids, 2009a; Glazier, 2021).
- Skill acquisition and motor control can enhance understanding of how coordinative structures are formed and how their morphology changes during learning (e.g., Vereijken et al., 1992, 1997), how practice design and training environments can be manipulated to accelerate their assembly and optimisation (e.g., Chow et al., 2011; Renshaw et al., 2019, 2020), and how the degrees of freedom comprising them re-organise as internal and external constraints change.
- Sport physiology and sport psychology can provide the methods and tools for measuring and analysing key functional organismic constraints, such as fatigue and anxiety, which have both been shown to have a substantial impact on the interaction and (re-)organisation of degrees of freedom at different levels of analysis (e.g., Bonnard et al., 1994; Collins et al., 2001; Forestier & Nougier, 1998; Higuchi et al., 2002).
- Motor development can provide insights into how structural organismic constraints, such as strength and flexibility, change across the lifespan (see Vandervoort et al., 2018, for a review of age-related changes affecting golfers) and how they impact on the patterns of coordination and control that characterise the golf swing. Movement variability and consistency have been identified as important issues, especially among the senior golfing population (Farrally et al., 2003). Research has shown that there is a change—typically a loss—of 'complexity' (i.e., flexibility/adaptability/variability) in biomechanical and physiological processes with age (Lipsitz & Goldberger, 1992), although this change is largely dictated by the confluence of constraints on action (e.g., Newell et al., 2006; Vaillancourt & Newell, 2002).
- Strength and conditioning can contribute to the augmentation or attenuation of structural and functional organismic constraints through carefully devised and implemented training interventions (e.g., Ives & Shelley, 2003). The contribution of this subdiscipline is important in physical preparation since any physical and physiological deficiencies or weaknesses in individual degrees of freedom may compromise the structural and functional integrity of its constituent coordinative structure, thereby potentially jeopardising its collective output. Additionally, restrictions on joint ranges of motion limit the number of body segment configurations that a golfer can adopt. The relaxation or removal of these constraints through mobility and flexibility training can increase the number of solutions available to that golfer. Functional movement screening may provide useful information for

guiding exercise prescription, although golf-specific tests, such as the Titleist® Performance Institute movement screen (Gulgin et al., 2014), still require further, more robust, validation.

- Sports engineering can provide insights into the physical properties and design characteristics of golf clubs, which represent key task constraints. As will be discussed in the 'Club design and customisation' section, golfer-club interactions (i.e., how the golfer biomechanically responds to changes in club properties and how the golf club responds to changes in swing biomechanics) have received limited coverage in the scientific literature but is a potentially valuable area of study given the direct implications for club design and customisation.

The above list is not intended to be exhaustive or definitive but, rather, it should be viewed as a guide as to how the various subdisciplines of sport and human movement science could work more interactively—using the constraints model advanced by Newell (1986) as a theoretical backdrop—to gain a deeper, more complete, understanding of golf performance.

Implications of adopting an ecological-dynamical approach for golf science

In the following sections, the implications of adopting an ecological-dynamical approach to golf science, specifically regarding swing biomechanics, club design and customisation, and coaching practice, will be considered.

Swing biomechanics

The biomechanics of the golf swing have received much coverage in the scientific literature (see Hume et al., 2005, and Glazier & Lamb, 2013, for scientific and coach friendly reviews, respectively). Although early empirical studies provided some useful preliminary insights, the research designs and analysis techniques traditionally adopted have arguably contributed little to knowledge advancement in recent years. The common strategy of reducing or collapsing biomechanical time series measurements to single data points, such as the peak angular velocity of a joint or the angular displacement of a body segment at a key moment (e.g., Chu et al., 2010), to facilitate statistical analysis has been a particular issue. This practice is commonplace in applied sports biomechanics research and has been justified if these time-discrete or zero-dimensional variables—known as *performance parameters* (Bartlett & Bussey, 2012)—are derived from a hierarchical or deterministic model of performance (see Figure 2). However, the removal of the remaining data points from the time series precludes insight into how a particular body segment moves throughout the swing, and, more importantly, how multiple body segments move in relation to each other throughout the swing. In other words, this approach provides very little information about how a golfer controls and coordinates his or her body segments, respectively, when executing a shot (see Sparrow, 1992, for elaboration of the distinction between coordination and control with specific reference to the golf swing).

Another issue with many extant biomechanical investigations of the golf swing is that they have adopted cross-sectional, group-based, research designs, where a very limited number of performance trials are collected, either from a single group of golfers of

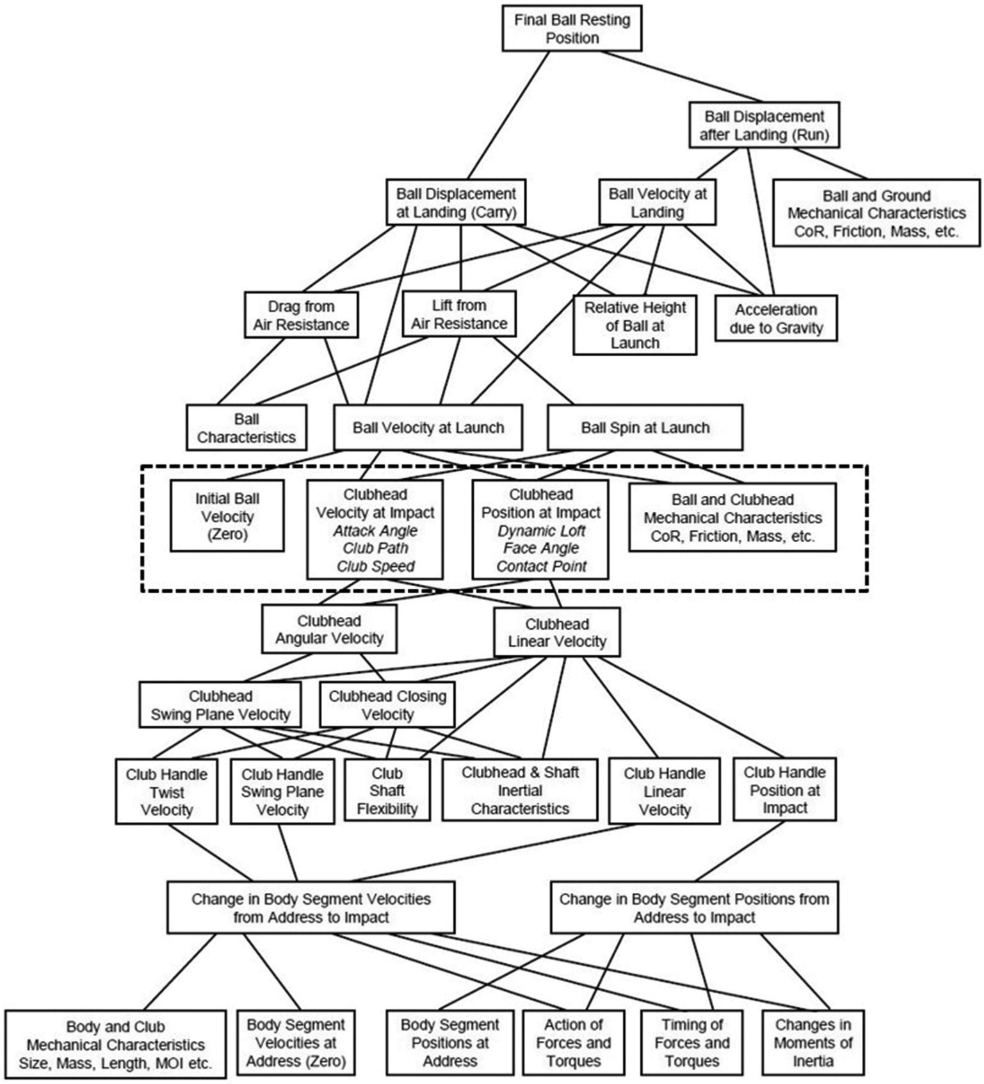

Figure 2. A hierarchical or deterministic model of a golf shot (adapted from Cheetham, 2014, with permission). The performance criterion ('final ball resting position') is identified at the top of the model and the factors that completely determine it ('ball displacement after landing (run)' and 'ball displacement at landing (carry)') are identified in the layer below. Each subsequent layer completely determines all the factors directly above it. The hashed box contains factors related to impact, which have particular significance to coaching practice as will be discussed in the 'Coaching practice' section. Despite being promoted in the golf science literature by Hume et al. (2005) and, more recently, by MacKenzie (2014) as a basis for evaluating technique, deterministic models are performance models not technique models and, as such, are inherently limited as they identify factors relevant to performance but not aspects of technique relevant to these factors (Glazier & Robins, 2012; Lees, 2002). In other words, these theoretical models identify *what* factors are important but not *how* these factors are produced. For example, this deterministic model suggests that a high clubhead speed at impact (the *what*) is an important performance parameter, but does not specify the movement patterns (the *how*) required to achieve a high clubhead speed for a specific golfer. As body segments can be coordinated and controlled in different ways to produce similar clubhead speeds (i.e., their interactions are indeterminate), body segment sequencing should not, by definition, be included in these performance models, contrary to the assertions of MacKenzie (2014).

comparable skill level (e.g., Burden et al., 1998), or two or more groups of golfers of different skill levels (e.g., Zheng et al., 2008) and/or on some other level, such as gender (e.g., Egret et al., 2006). In a single-group design, performance parameters are typically correlated with the performance criterion or outcome measure, such as clubhead speed, ball speed, or distance hit—all of which have been shown to be strongly related to skill level (e.g., Fradkin et al., 2004)—whereas in a multiple-group design, mean differences in performance parameter data are calculated and compared across groups. Again, these *correlation* and *contrast* approaches (Glazier & Mehdizadeh, 2019a) are commonplace in applied sports biomechanics research because they purportedly enable inferences to be made about the wider population of golfers from which the study samples were drawn, thus facilitating the development of putatively generalisable laws and principles that govern the golf swing. However, the results of these group-based analyses cannot necessarily be applied to *individual* golfers because the patterns of coordination and control generating the data are unlikely to be *ergodic* owing to variability in technique within and between golfers (see Fisher et al., 2018). Of course, the research designs typically used in biomechanical studies of the golf swing do not permit formal assessment of ergodicity because, in addition to not routinely analysing patterns of coordination and control, the pooling of individual data masks inter-individual variability, and the reliance on a single 'best' or a putatively more 'representative' average trial precludes the analysis of intra-individual variability.

To overcome the aforementioned issues and to develop knowledge to aid the optimisation of individual golfers' swings, alternative research designs and analysis techniques need to be explored. One approach that has featured in several recent ecological-dynamical investigations of human movement is *coordination profiling* (Button et al., 2006; Davids et al., 2003; Glazier et al., 2003). This approach combines analytical methods, such as continuous relative phase, vector coding, self-organising maps, cluster analysis, and principal component analysis (e.g., Federolf et al., 2014; Schöllhorn et al., 2014; Wheat & Glazier, 2006), that are capable of examining multiple time series datasets simultaneously, with a repeated measures research design (see also Caldwell & Clark, 1990, for a detailed exposition of how more traditional biomechanical analysis methods can be used to evaluate technique from an ecological-dynamical perspective). Indeed, continuous relative phase and vector coding have already fleetingly been used, for example, to examine differences in pelvis-thorax coordination between male and female golfers (Horan et al., 2011), amateur and professional golfers (Sim et al., 2017), and when hitting to different distances using the same club (Lamb & Pataky, 2018). Additionally, self-organising maps have been used to examine changes in inter-limb coordination during the performance of chip shots to different distances (Lamb et al., 2011). By adopting these more progressive approaches, golf researchers will be better equipped to identify the patterns of coordination and control that produce the best performance outcomes for individual golfers. As it is currently not possible to computationally determine golfer-specific optimum techniques (see Glazier & Davids, 2009b; Glazier & Mehdizadeh, 2019b), coordination profiling may offer the most efficacious method of 'optimising' swing mechanics, especially if kinematic and kinetic data are combined with club delivery and ball flight measurements (see the 'Coaching practice' section).

Club design and customisation

It has previously been argued that golfer-club interactions are too crudely understood to enable clubs to be fitted properly (Farrally et al., 2003). Most equipment-related studies, to date, have been limited to comparisons of swing biomechanics when using different golf clubs, such as irons and woods (e.g., Egret et al., 2003; Nagao & Sawada, 1973; Sinclair et al., 2014; Wallace et al., 2004). However, many of these investigations have been based on the paradigms criticised in the 'Swing biomechanics' section and have, therefore, tended to be narrow in scope and have yielded somewhat superficial findings. For example, Sinclair et al. (2014) showed that, although swing kinematics were broadly similar across clubs, clubhead speed at impact was significantly greater, stance at address and top of backswing was significantly wider, and torso, hip, and knee angles at address were significantly more extended, when using a driver compared to a 9-iron and a 6-iron (see Egret et al., 2003, for similar findings).

Two noteworthy investigations that demonstrate the virtues of adopting a more individualised approach when evaluating golfer-club interactions were the studies of Haeufle et al. (2012) and Worobets and Stefanyshyn (2012). In the former study, the effect of adding mass to the shaft on clubhead speed in a group of low-handicap golfers was examined. By adding 22 grams, or 7 percent, of mass to the shaft, a 2 percent decrease in clubhead speed was predicted based on the output of a mechanical double pendulum model. However, of the 12 golfers tested, one golfer produced significantly reduced clubhead speed (−1.4 percent), another golfer produced a significantly increased clubhead speed (+3.0 percent), whereas the other golfers exhibited little or no change in clubhead speed when swinging the heavier driver compared to the lighter driver. It was concluded that golfers do not respond to changes in club mass properties in mechanically predictable ways. In the latter study, the influence of shaft stiffness on clubhead speed in a group of 40 golfers was examined. It was found that, on average, there was no significant difference in clubhead speed between drivers with shafts of different stiffness. However, when data from individual golfers were analysed, significant differences in clubhead speed were found for 27 golfers, with the average largest difference in clubhead speed between drivers being 2.6 percent (1.5–5.0 percent). Seventeen golfers produced their highest clubhead speeds with one of the two drivers with the most flexible shafts, whereas only four golfers produced their highest clubhead speeds with one of the two drivers with the stiffest shafts. The results of these two studies collectively indicate that the properties of golf clubs can have a large impact on performance but are dependent on how a golfer loads the club, which are, in turn, dictated, in large part, by the golfer's organismic constraints, specifically the force-length and force-velocity relationships of skeletal muscle (see Stefanyshyn & Wannop, 2015).

The properties of golf clubs that contribute to their perception during the golf swing have received sparse coverage in the scientific literature. Previous investigations into the 'feel' of golf clubs have largely been limited to the examination of the haptic and acoustic information produced and transmitted during club-ball impact, and golfers' subjective interpretation of that information (e.g., Hedrick & Twigg, 1995; Hocknell et al., 1996; Roberts et al., 2005a, 2005b). One of the few exceptions in the literature, however, was the study of Harper et al. (2005), which examined the effect of swingweight on the perception and performance of drivers. Swingweight provides a measure of weight distribution and is considered to be the industry standard for 'matching' golf clubs across a set (see Figure 3a for a schematic detailing how swingweight is measured). Based on data obtained from 30 skilled golfers using four drivers of different swingweights (C7, D0, D5, E0), Harper et al. (2005) concluded that the golfers, on average, were unable to perceive small changes in swingweight (±3 points) and that these changes had little impact on player performance in terms of clubhead speed and impact location. However, on closer inspection of the available data, over half of category one (<5 handicap) golfers were able to distinguish between the drivers with the smallest difference in swingweight (C7-D0). Although it is not possible to determine whether the increased sensitivity to changes in swingweight materially impacted on performance for these particular golfers, these insights further demonstrate the need to adopt an individual-specific approach when studying golfer-club interactions.

An alternative to swingweight matching, which has only been used sparingly in the custom fitting of golf clubs and has seldom featured in the scientific literature, is moment of inertia matching. The moment of inertia of a golf club can be defined as the resistance to rotational acceleration about an axis at the butt end of the grip that is approximately

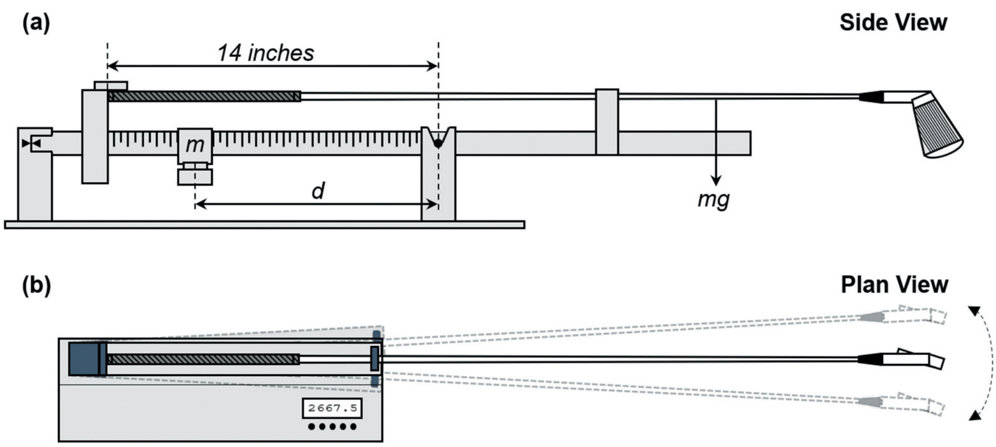

Figure 3. (a) The swingweight of a golf club is commonly defined as the first moment of mass about a fulcrum 14 inches from the butt end of the grip and is measured using a 'lorythmic' swingweight scale (analogue version shown). When mounted on the scale, a moment is generated about the fulcrum by the weight, *mg*, of the club. The sliding mass, *m*, is then positioned to balance the club moment. Swingweight is calculated by multiplying, *m*, by its distance, *d*, from the fulcrum and the resulting number being divided by two (i.e., two inch-ounces represent one swingweight). Alpha-numeric values ranging from A0 to G9 (i.e., A0-A9, B0-B9, . . . , G0-G9) are used to designate swing-weights with each swingweight point being progressively heavier than the preceding swingweight point. (b) The moment of inertia or second moment of mass of a golf club is defined as the resistance to rotational acceleration about an axis at the butt end of the grip that is approximately normal to the swing plane at impact and is commonly measured using a compound cantilevered device. Once clamped to the cantilever, the club is retracted and released, allowing it to oscillate back and forth. The cycle period, *t*, is measured and, with the known elastic constant, *k*, of the previously calibrated internal spring, the moment of inertia, *I*, of the club is calculated ($I=k[t/2\pi]^2$) and displayed on the digital readout.

normal to the swing plane at impact (see Figure 3b for a schematic detailing how moment of inertia is measured). Both mechanical engineers (e.g., Budney & Bellow, 1982) and club fitters (e.g., Wishon, 2011) have suggested that moment of inertia is the only method of truly matching golf clubs and ensuring they have identical swing 'feel'. The use of moment of inertia in the custom fitting of golf clubs is further supported by psychophysical research, most notably in studies of *dynamic touch* (Gibson, 1966), which have identified moment of inertia as a haptic invariant (see Carello & Turvey, 2000, 2017; Turvey & Carello, 1995, 2011 for comprehensive reviews and also Kim et al., 2013, for a case study examining wrist positioning at the top of the back swing using the dynamic touch concept). Although preliminary findings reported by MacKenzie et al. (2016) indicated no performance differences between swingweight and moment of inertia matched golf clubs, further research similar to that conducted on tennis racket (e.g., Carello et al., 1999) and ice hockey stick (e.g., Hove et al., 2004, 2006) usage would increase understanding of golfer-club interactions and potentially enhance the custom fitting process, particularly for junior and senior golfers. For example, golf clubs could be fitted according to the affordances they offer the golfer using them—that is, woods and long irons could be fitted with inertial characteristics that the golfer deems to afford power hitting whereas short irons and wedges could be fitted with inertial characteristics that the golfer deems to afford precision hitting. This somewhat esoteric and complex area of study should be of great interest to golf club manufacturers, especially if tangible performance benefits can be demonstrated, given that the scope for innovation in most other aspects of golf club design is extremely limited due to the regulations imposed by golf's governing bodies.

Coaching practice

A view held by some golf coaching practitioners is the existence of an optimum or ideal golf swing that should be achieved if peak performance is to be realised and injury risk is to be minimised. This perspective has been reflected in numerous coaching texts and instructional videos, which have tended to emphasise a standard grip, stance, backswing, downswing, and follow-through. Even putatively more scientific approaches have attempted to identify an optimum or ideal golf swing that can be used for comparative purposes to identify faults and specify remedial action. For example, Mann and Griffin (1998) formulated a composite model called the 'ModelPro' based on the average of 100 US PGA, LPGA, and Senior PGA Tour players' swings, that they championed as *the* template or criterion golf swing that all golfers should strive to achieve. Similarly, Ae et al. (2021) created a 'standard motion model' based on the averaged three-dimensional kinematics of 25 skilled golfers' swings, which they claimed could be used as a basis for teaching the driver swing. However, a casual observation of some of the game's greatest players, such as major championship winners analysed by Mann and Griffin (1998) that included Paul Azinger, Raymond Floyd, and Jim Furyk, reveals considerable differences in their golf swings, implying that a one-size-fits-all model may not be an effective instructional strategy owing to variations in organismic constraints. Given that golfers can exhibit marked differences in their swings but, yet, are still able to achieve high levels of performance, how can golf coaching practitioners effectively evaluate technique to accurately diagnose faults and reliably distinguish them from idiosyncrasies or functional adaptations? What strategies can golf coaching practitioners adopt to enhance the performance of their students?

One strategy would be to use club delivery parameters as augmented information to channel the golfer's search towards his or her own 'optimal' swing (e.g., Newell et al., 1989; Newell & McDonald, 1992; Pacheco et al., 2019). This approach aligns with the philosophies of some of the game's most eminent coaching practitioners (e.g., Jacobs, 2005) and coach educators (e.g., Wiren, 1991) who have also recognised the primacy of impact. As identified in the deterministic model shown in Figure 2, the outcome of a golf shot is related to the initial launch conditions (assuming neutral environmental conditions), which are, in turn, directly related to the impact conditions, most notably the clubface-to-path relationship (see Figure 4 for an elaboration of how impact affects ball flight). Club delivery parameters can be easily and reliably measured using launch monitor technology and can provide guidance about the types of technical adjustments that may achieve more functional club delivery at impact and, therefore, better shot outcomes. The golfer, with or without the input of a coach, can explore different combinations of body segment motions and observe concomitant changes in club delivery parameters. If a particular technical change has no material effect on club delivery, it can likely be disregarded as it provides no tangible performance benefit. Once more functional club delivery has been achieved, the golfer can attempt to recreate,

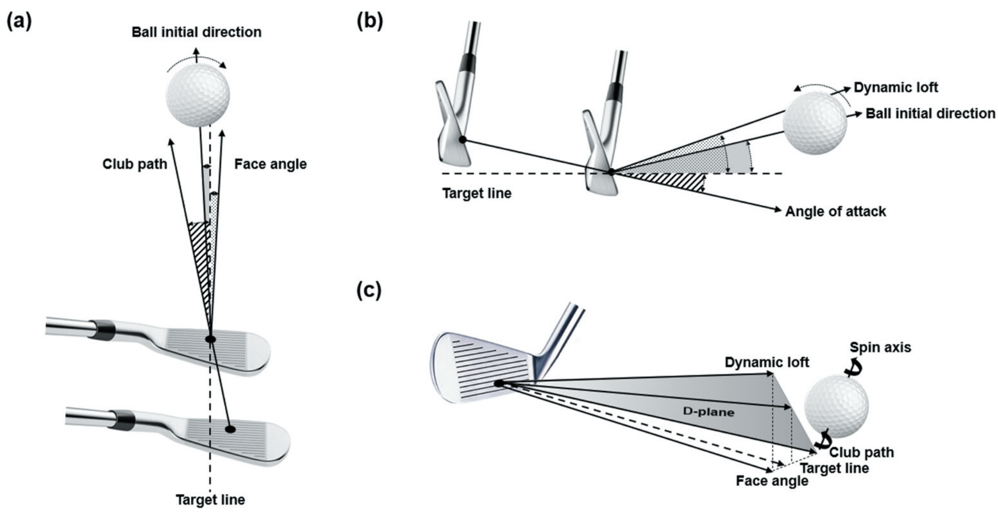

Figure 4. Club motion in the (a) horizontal and (b) vertical planes combine to create the (c) D-plane during club-ball impact. The club-ball impact phase lasts approximately .5 milliseconds (Cochran & Stobbs, 1968) and determines ball launch, which subsequently determines the outcome of a golf shot (assuming neutral environmental conditions). Wood et al. (2018) calculated that the average horizontal launch angle was 61–76 percent towards the face angle from the club path and the average vertical launch angle was 72–83 percent towards the dynamic loft from the angle of attack (differential known as spin loft) based on data collected from golfers and a golf robot swinging a driver, a 7-iron, and a 58-degree wedge. The D-plane, first described by Jorgensen (1999), determines the spin axis of the golf ball at launch, which will be orthogonal to the D-plane for centre impacts. The rate of spin around the spin axis combined with the initial launch velocity determine the curvature of the ball flight trajectory.

refine, and stabilise the patterns of coordination and control that produced it over iterative shots during practice. In effect, club delivery parameters derived from launch monitor technology can be used to calibrate patterns of coordination and control without making explicit reference to them. To support the calibration process, biomechanical (kinematic and kinetic) feedback describing the golf swing can be used to supplement club delivery parameters, although its role is largely incidental and may simply be to make more salient aspects of coordination and control that would otherwise go undetected (Brisson & Alain, 1996).

A key reason why ecological-dynamical proponents favour this *guided discovery approach* over more traditional prescriptive instruction is that, in addition to the fact that markedly different patterns of coordination and control can produce the same club delivery parameters, predicting whether a given technical change will lead to consistently better club delivery for an individual golfer is challenging owing, in large part, to his/her unique *intrinsic dynamics*. These intrinsic dynamics—described by Thelen (1995) as the *'preferred states of the system given its current architecture and previous history of activity'* (p. 76)—provide the backdrop to learning upon which the new or modified pattern of coordination and control must be developed. However, the extent to which the new or modified pattern of coordination and control can be reliably adopted depends on both the layout and topography of the attractor landscape representing the golfer's intrinsic dynamics (e.g., Kostrubiec et al., 2012). If the attractor corresponding to the golfer's existing swing is well-developed (i.e., if existing patterns of coordination and control are stable and robust), substantial changes will likely be difficult to attain. Similarly, if the attractor corresponding to the swing the golfer is attempting to adopt is not in close proximity to the attractor corresponding to the golfer's existing swing (i.e., if the two patterns of coordination and control are markedly different), the former is unlikely to be attainable irrespective of the amount of practice undertaken (Corbetta & Vereijken, 1999; Kostrubiec et al., 2012; Zanone & Kelso, 1992). Importantly, in both scenarios, any attempt to modify the pattern of coordination and control through extended practice will change the characteristics of the existing attractor, possibly irreversibly. Anecdotally, this account of skill development may explain why some previously successful elite golfers, including major championship winners (Barkow, 1998), have not only been unable to successfully adopt desired technical changes, but then have subsequently been unable to rediscover the swing that brought them success in the first instance.

Concluding remarks

This paper has considered how golf science could be informed by the ecological-dynamical approach. Although issues regarding the integration of ecological psychology and dynamical systems theory remain (see Beek & van Wieringen, 1994; Beek et al., 2003; Michaels & Beek, 1995), the analysis provided here suggests the ecological-dynamical approach has the potential to make a significant contribution to the enhancement of knowledge and understanding of swing biomechanics, club design and customisation, and coaching practice. Additionally, it can provide a platform on which to integrate the various sub-disciplines of sport and human movement science to gain a more holistic understanding of golf performance. It is, therefore, recommended that golf scientists explore the virtues of the ecological-dynamical approach in future studies of the human element of the sport.

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