EFFECTIVE SKILL REFINEMENT: FOCUSING ON PROCESS TO ENSURE OUTCOME

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Abstract. In contrast to the abundance of motor skill acquisition and performance research, there is a paucity of work which addresses how athletes with an already learnt and well-established skill may go about making a subtle change, or refinement, to that skill. Accordingly, the purpose of this review paper is to provide a comprehensive overview of current understanding pertaining to such practice. Specifically, this review addresses deliberately initiated refinements to closed and self-paced skills (e.g., javelin throwing, golf swing and horizontal jumps). In doing so, focus is directed to three fundamental considerations within applied coaching practice and future research endeavours; the intended outcomes, process and evaluative measures of skill refinement. Conclusions suggest that skill refinement is not the same as skill acquisition or performing already learnt skills with high-levels of automaticity. Due to the complexity of challenge faced, refinements are best addressed as an interdisciplinary solution, with objective measures informing coach decision making.

Key words: Technical change, pressure resistance, long-term permanency, the Five-A Model, movement variability

Introduction

For over 100 years researchers have attempted to understand the mechanisms which enable the attainment and execution of skilled performance (for a historical overview see Summers 2004). More recently, there has been substantial growth of interest directly pertaining to the acquisition and optimal performance of sports skills (e.g., Ericsson et al. 1993; Hodges and Franks 2002; MacPherson et al. 2008; Mesagno and Mullane-Grant 2010). As a consequence of such theorising (e.g., Fitts and Posner 1967; Gentile 1972) and researching, coaches are afforded the potential to be guided by a scientifically informed evidence-base. Unfortunately, however, there has been an almost complete neglect towards an equally well known and common task to elite-level athletes and their coaches; namely, how to change the technique of an already learnt and well-established skill.

Indeed, despite an aberrantly high skill status, elite athletes still invest much time and effort to tweak or *refine* their technique. As part of any elite athlete's training programme, technical refinements form an almost inevitable component of striving to improve performance. Previously, we defined technical refinement as reflecting "the evolution of technique in a way that is *new* [emphasis added] to the athlete" (Carson and Collins 2011, p. 147). In some unfortunate cases, this might be forced by injury concerns or as part of the recovery process, as exemplified by Olympic heptathlete Jessica Ennis-Hill (changing the take-off foot to her long jump). Reflecting the multitude of underpinning rationales for refinement, Olympic javelin thrower Steve Backley alluded to motivational benefits that were gained by frequently "re-inventing" himself (and his technique) as a way of staying "interested" (BBC 2007, section 9). Other reasons might include a response to changes to task constraints (e.g., longer golf holes, new club designs or new javelin designs), or advances made by competitors. Such broad scope of rationale attests to the widespread implementation of refinements at the elite level and requirement for coaches to possess both declarative ('what needs to be done') and procedural ('how to do') knowledge on the topic.

Accordingly, this paper focuses on deliberately initiated technical refinements – not changes to technique caused by short-term performance-related perturbations – to closed and self-paced skills (e.g., javelin throwing, golf swing and horizontal jumps). In an attempt to provide a comprehensive overview of current understanding, three fundamental considerations are presented; the intended outcomes, process and evaluative measures of skill refinement. Understanding of all three will enable coaches and their athletes to make informed decisions about the required training. Indeed, this desire for the highest quality of coaching practice reflects the overarching purpose behind our research programme in this topic.

Essential outcomes of effective skill refinement

Before considering the process of implementing skill refinement, it is worth highlighting several outcomes that make such refinements effective. Reflecting the challenges faced by competitive elite-level athletes, these outcomes *should* represent desirable and realistic performance goals; despite current evidence showing that this is often not the case (e.g., in elite-level golf; Carson et al. 2013). Accordingly, we recommend that future research which aims to inform applied coaching practice, attends to these outcome criteria as established 'gold standards', dual rooted in motor control (Newell et al. 2001) and sport psychology (Cheng et al. 2009) theory. Furthermore, integration between these two domains can provide a greater understanding of the cognitive – co-ordinative dynamics which underpin skill development (Kelso 1995; Schack and Bar-Eli 2007). Crucially, therefore, interdisciplinary research is most likely to offer a complete account to practitioners.

Kinematic Change

Central to refining technique in elite athletes, is the requirement for kinematic modification to an already learnt and well-established skill. Therefore, it is essential that studies report kinematic data pertaining to the intended refinement (e.g., Carson et al. 2014a). Unfortunately, however, this has not always been the case within empirical studies. For instance, Hanin et al. (2004) provide a detailed theoretical rationale and intervention design to refine the diving technique of an Olympic swimmer, yet results only pertain to improvements in starting time. Similarly, Rendell et al. (2011) focused their kinematic analysis on the netball's flight to represent evidence of technique adaptation in National goal shooters. While these studies undoubtedly show pre- to post-intervention differences (although not as desired in Rendell et al.'s study), they fail to have reported on the variable of stated interest, the athletes' intended technical refinement. By comparison, study of this nature is less common when exposing psychophysiological mechanisms associating, for instance, visual search and attentional focus (e.g., Wood and Wilson 2011); whereby, researchers would be expected to report eye tracking data at the very least to represent participants' visual search strategy. As such, research which addresses the modification of movement kinematics surely should not dismiss the necessity of employing kinematic measures to provide this evidence (cf. Peh et al. 2011).

Moreover, by its very nature, refinement to an individual's already learnt and well-established skill is likely to involve a change that is highly specific to each individual. This is particularly supported by evidence which shows high-level athletes to demonstrate inter-individual differences in technique (e.g., Chow et al. 2006; Schorer et al. 2007), reflecting the combined organismic, task and environmental constraints imposed on performers during skill acquisition (Newell 1986). Therefore, based on theoretical and empirical guidance, analyses of effects are best presented, and understood in terms of the nuances which separate coaching practices required for different athletes, as individual case studies.

Pressure resistance

Inevitability within elite-level sport, peak performance requires the successful execution of a skill in highly competitive and pressurised environments. As such, simply demonstrating successful execution of a newly refined technique is insufficient. Rather, execution must remain transferrable under symptoms of high competitive pressure in order to be considered wholly successful. Instead of this being an issue of kinematic effectiveness, it is one of control *and* psychological state; specifically, the extent to which a performer possesses high levels of automaticity (i.e., without requirement for too much conscious attention; Dougherty and Johnston 1996; Singer 2002) *and* self-efficacy.

From an anecdotal perspective, there are numerous exemplars of when a refinement has not been made resistant against the negative effects of competitive pressure; the results of which can be career ending. For example, golfer Craig Perks, winner of the 2002 Players Championship (largely considered the highest ranking tournament outside of the four Majors), undertook a swing change shortly following victory in the hope that it would increase his shot consistency. According to Perks, he "was sick and tired of being sick and tired... I was so frustrated with how stagnant my game had become or how inconsistent" (Alexander 2003, para. 10). Reporting on the immediacy of effect following the introduction of a new coach, Perks added:

> I've been trying to do something in my golf swing, actually trying to flatten my left wrist, for about nine years, and within two swings we had it as good as I'd ever had it. So right there and then I knew we were on the right track (Alexander 2003, para. 23).

Despite an initial ability to demonstrate the desired technique (as shown by the kinematic criterion), Perks' inability to re-establish automaticity and self-efficacy during competitive play, ultimately resulted in a decline of earnings (Figure 1; PGA Tour 2014) and retirement from professional golf following the 2007 season. Perks confirms this by explaining:

> the worst mistake I made was trying to change my swing... I became so screwed up that I wasn't playing golf anymore. I was standing over the ball and thinking mechanics, what I was supposed to do. I was playing golf swing instead of golf (Verdi 2012, para. 8).

Empirically, the literature provides a strong case for demonstrating the fragility of automated skills under pressurised conditions when utilising high-levels of conscious control. The work of Beilock and colleagues (e.g., Beilock et al. 2004a; Beilock et al. 2004b; Beilock and Carr 2005) has suggested that distraction (Eysenck et al. 2007) *and* self-focus (Masters 1992; Beilock and Carr 2001) can mediate failure of a normally successful and subconsciously controlled execution; representing a "double whammy" effect (Beilock et al. 2006: 1062). Specifically, worried athletes become distracted by task-irrelevant thoughts (first whammy; attention towards task-relevant information is compromised). Consequently, this tempts athletes to increase conscious attention to the skill in a step-by-step fashion which disrupts automated control (second whammy; attention allocation is counterproductive). Supporting the second of these whammies, Masters and Maxwell (2004) operationalised the term "reinvestment" as the "manipulation of conscious, explicit, rule based knowledge, by working memory, to control the mechanics of one's movements during motor output" (p. 208). Accordingly, consciously *controlling* the technique is suggested to underpin performance failure, particularly under conditions of high anxiety which provoke self-consciousness and evaluation (Masters and Maxwell 2008). Expanding further on this disruptive self-focus effect, however, another whammy is apparent! Consciously overemphasising individual components of an established technique has been shown to result in an almost inevitable under-emphasis of others (cf. MacPherson et al. 2008; Carson et al. 2014b); a detail which is unaccounted for within these theories.

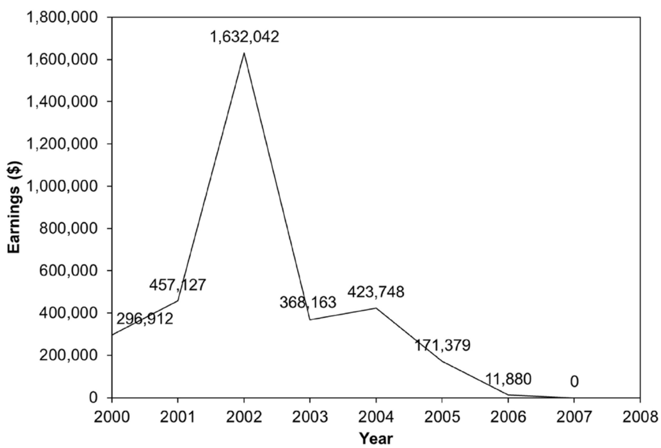

Figure 1. Seasonal earnings of Craig Perks on the PGA Tour
Source: Data sourced from PGA Tour (2014).

Exemplifying the criterion of pressure resistance within the applied literature, Collins et al. (1999) evidenced the transferable ability of an Olympic-level javelin thrower maintaining a technical change at Olympic and European Championship qualifiers, as well as the Olympic Games. Likewise, Carson et al. (2014a) presented both kinematic and self-efficacy data for an Olympic-level weight lifter subsequently executing their refined snatch lift technique at British and European Championships following return from injury.

This requirement for pressure resistance is not dissimilar to that of *transfer* which is usually employed in skill acquisition studies (e.g., de Boer et al. 2013). In fact, we categorise pressure resistance as a *de facto* measure of transfer when working with elite athletes. Crucially, due to elite athletes performing in situations that have greatest potential for high competitive pressure, combined with the fact that performance within these environments most typically account for when automatic control of technique goes awry, coaches must ensure that the execution of a refined technique is not susceptible to such debilitating mechanisms. As a demonstration of the realistic difference between training and competitive states, MacPherson et al. (2008) reported most dissimilarity in mental focus and kinematic variability measures within International javelin throwers compared to an Olympic-level; indicating a less than similar bodily state between the two conditions. This idea of a training body or a competition body fits with anecdotal reports and coaching actions, and holds significant implication for coaches in self-paced, closed skill events.

For the present, however, we suggest that researchers and/or practitioners assess elite athletes more stringently when compared to those methods normally applied within experimental research designs (e.g., executing a skill with the contralateral limb; Lawrence et al. 2011). Such assessments should reflect most typically the challenges (both mental and physiological; Cheng et al. 2009) likely to be faced within competition, or if possible the competition itself (although not without proactively priming the athlete, see Section 'Implementing technical refinement in elite performers: the Five-A Model').

Long-term permanency

Following many hours of training, it is well acknowledged that learnt skills are characterised by individually-preferred, automatic and stable (i.e., consistent) movement patterns, with a reduction in the random variability more commonly found in novices (Gentile 1972; Müller and Sternad 2004). Underpinning this high-level of stability are numerous morphological changes, including; structure of neurological substrates (Wu et al. 2008), metabolic efficiency (Sparrow et al. 1999) and cognitive processes (Anderson 1982). Consequently, when a goal-directed and self-paced skill is learnt, effective organisation between these subsystems leads to a lower state of global entropy (Cordier et al. 1994). Establishing a high-level of movement stability is not only represented by easier, faster, more accurate and efficient execution of technique, but also *long-term permanence* – all of which increase the likelihood of producing consistently superior performances. Salmoni et al. (1984) suggest that for movements to be classified as learnt, they should persist over time scales of months, if not years. Unfortunately, such efficient and long-term permanent characteristics also present a challenge of probable regression when attempting deliberate refinements; a less apparent factor when *acquiring* skill and similar levels of control.

Reflecting this regression, experienced cyclists have been shown to gravitate back towards an individually-preferred natural cadence on removal of a metronome-induced rhythm (MacPherson et al. 2007). Jenkins (2008) also reported European Tour professional golfers to be *incapable* of changing their putting strokes under conventional coaching instruction; a difficulty which is corroborated by field athletics coaches (Trower 1996). Huys et al. (2009) further substantiate the implications of possessing a well-established technique when implementing a refinement:

> it could be expected that the athlete would encounter difficulty in achieving the adopted aim [targeted technique] as the inferior [previous] technique may remain present as a ghost or remnant of a stable solution... and thus may continue to affect coordination (p. 359).

Indeed, this challenge is particularly critical when the need for refinement is associated with an injurious movement pattern (cf. Carson et al. 2014a); either as a preventative measure to future injury or when returning from an injury caused by poor technique. In fact, it is worth noting that, as a performer gains more experience (and undergoes more changes) the number of ghosts may well increase, meaning that such interference is logically a more common problem for more experienced performers. The greater number of injuries almost inevitably associated with such greater experience merely serves to exacerbate the problem. The bottom line of this is that care must always be taken to 'eliminate' the ghosts when new moves are learnt. Without such 'skill housekeeping' the older performer may end up with a veritable haunted mansion!

Despite Salmoni et al.'s (1984) recognised view that learning should persist for months, if not years, before a skill is categorised as being leant, long-term permanence is not commonly reported within the literature. Rather, absolute retention tests are typically administered to evaluate how much learning has taken place (e.g., Li and Wright 2000); that is, the level of performance retained following an interval of no practice, usually measured in minutes, hours or days. These time scales *might* be appropriate when assessing the acquisition of skills for theoretical research purposes. However, due to the continuous engagement by elite athletes in sport, provision for warm-up behaviours and requirement for long-term permanence of technique, it is questionable whether relatively short-term absolute retention tests are appropriate for assessing technical refinement. Instead, adopting principles associated with 'saving score' tests (Christina and Shea 1993) *could* provide a more meaningful indicator to athletes and coaches. Saving score assesses the number of trials required following an interval, between training sessions perhaps, to execute a desired level of performance, or technique in this case. Since elite-level athletes are likely to suffer regression effects (to greater or lesser extents), saving score may provide a more meaningful measure of technique stability during a warm-up period (i.e., habituation effect), as this would also confirm the existence of the refined technique. In contrast, absolute retention does not necessarily leave athletes meeting their goals, or at least part of them (i.e., kinematic criterion). In any case, we extend Salmoni et al.'s suggestion by recommending that technical refinements must also be demonstrated over time scales of months, if not years, before an intervention's level of success may be fully evaluated.

In view of this need to demonstrate long-term permanency of technical refinements, previous applied research has reported follow-up kinematic data after periods of years (Collins et al. 1999; Carson et al. 2014a) and months (Carson and Collins under review). However, time scales have not always been reported in more fundamentally oriented 'post-test' studies (cf. Rendell et al. 2011). Consequently, irrespective of outcome, such investigations offer no guidance to practitioners on the resultant long-term permanency and/or whether the technique regressed back to a previous version.

Coaching knowledge as 'joined up thinking': linking outcome to process

Having outlined what we suggest are essential skill refinement outcomes, the next section turns its attention to the process through which these outcomes may be achieved. Such understanding between outcomes and process are paramount, and relies on practitioners' ability to translate theory into practice; based on current evidence, such translation is suggestively weak. For example, Partington and Cushion (2013) found youth soccer coaches to possess low self-awareness of their behaviours and link between declarative and procedural knowledge. This was exemplified by an "epistemological gap" or "cognitive dissonance" (Light 2008: 26) when discussing the need, but not understanding how, to develop soccer players with effective decision making skills. Consequently, coaches often reverted to coaching based on tradition, intuition and imitation of others (Schempp et al. 2006). Similarly, expert golf instruction has been reported as largely intuitive with a lack of reference to applied scientific evidence-bases, whereby the primary sources of knowledge are derived from other coaches and previous experience (Schempp et al. 1998). Indeed, Carson et al. (2013) reported a lacking in comprehension of the 'ologies' when European Tour golf coaches implemented skill refinement. Notably, applied practice needs to be underpinned by sound theory, even when coaches are working tacitly (cf. Nash and Collins 2006). The guiding principle is that, unless coaches are able to understand *why* a particular coaching method should be employed for a certain problem against a plethora of other alternatives, they will be unable to effectively advise, evaluate and adapt their practices for different performer needs (Abraham and Collins 2011a). Therefore, the following section provides such rationalisation when implementing refinements to already learnt and well-established skills.

Implementing skill refinement in elite-level athletes: the Five-A Model

Skill refinement, as with any process involving human development, invariably depends on the combined influences of biological, psychological and sociological factors. Indeed, Collins et al. (2012) when referring to athlete development in sport, suggest that "effective models and effective interventions are almost of necessity required to address all three components and their interaction. In short, the biopsychosocial approach offers an effective basis for modelling and manipulating this crucial but complex facet of human behaviour" (p. 237). Therefore, if the essential outcomes for effective skill refinement are to be achieved, an interdisciplinary method is required. More precisely, are the significant gains that can be achieved by considering the fields of motor control, biomechanics and sport psychology; arguably, these *should* form fundamental sources of knowledge within applied coaching practice (Abraham et al. 2006).

Reflecting this need, the most comprehensive solution to date is the Five-A Model, derived from the extant literature by Carson and Collins (2011). Mechanistically underpinned by principles of motor control, the model proposes three sequential stages. Firstly, the 'Awareness stage' serves to de-automate the existing skill by calling into consciousness the component of technique requiring refinement. This highly-conscious step is considered essential to initiating the departure process from the current to desired technique. Explicit *contrast* between the two versions intends to perturb the stable state of system organisation. Without delineating a distinct alternative, the likelihood is a rapid regression back to the original technique (cf. Kostrubiec et al. 2006). Contrary to research investigating the optimal *performance* of learnt motor skills (e.g., Perkins-Ceccato et al. 2003; MacPherson et al. 2008; Bell and Hardy 2009) – which promotes the use of subconscious control – support for this temporary (conscious) perturbation is strongly apparent across many domains which address 'change' in general; including, counselling (Bar-Eli 1991), reorganisation of neural networks (Mercado 2008; Butz et al. 2009) and business growth (Evans 1994). Indeed, other motor control researchers share this view, suggesting that "in reshaping the imperfect automatisms it seems initially necessary to intentionally deautomatize movement control" (Oudejans et al. 2007: 41). Exemplar techniques within the Five-A Model to achieve de-automation include contrast drills, self-report and visual and kinaesthetic imagery (facilitated by self-observation). We should point out that although kinematic modification is an essential outcome of effective skill refinement, from the athlete's point of view this process is likely to be driven by a kinetic difference which is monitored through kinematics.

Once the skill is de-automated, the 'Adjustment stage' gradually modifies the kinematics towards the target behaviour. Whereas the Awareness stage is dramatic in nature, the Adjustment stage is defined by small shifts in difference. With a representation of the targeted technique already delineated, albeit with a relatively weak level of stability, this stage facilitates greater acceptance, comfort and accuracy of the intended refinement while concurrently weakening those of the original version. Indeed, Tallet et al. (2008) observed that bistable (0° and 180°) participants learning a 135° relative phase bimanual co-ordination pattern, initially stabilised a pattern close to 90° and then *shifted* toward 135°. In practice, Carson et al. (2014a) employed a progressive 'shaping' methodology based on visual and kinaesthetic imagery informed by an observed best self-model. Similarly, Collins et al. (1999) faded out the ratio of incorrect versus correct contrast drills, systematically increasing demands to demonstrate the correct version. Assessed through self-report, the Adjustment stage is typified by a growing preference for the new version technique and unfamiliarity with the old.

Following consistent achievement of the target technique, the '(Re)Automation stage' aims to return the athlete to executing with largely subconscious control. This stage is supported by the large volume of work examining performance failure when employing conscious control strategies (Masters 1992; Beilock et al. 2004a; Beilock et al. 2004b; Masters and Maxwell 2008), as discussed earlier. From a practical perspective, the Five-A Model encourages re-automation through the use of holistic rhythm-based cues (cf. MacPherson et al. 2008; MacPherson et al. 2009). Rhythmic cues which summarise the movement's entirety, by emphasising the temporal structure, provide athletes with an 'aide-memoire' to reduce their focus towards the refinement and restore stability across all components of the skill. Thus, rhythm is a *source of information* that does not overly tax working memory, permitting attention to also be directed towards other task-relevant stimuli.

When actions are congruently informed by auditory, kinaesthetic and visual stimuli (i.e., multisensory processing), neural responses exceed the sum of unisensory inputs; an effect known as *superadditivity* (Stein and Meredith 1993), which is particularly apparent when the salience of individual sensory signals weaken (Stanford et al. 2005). Applying the same principle to mental imagery use, this would, however, be an inevitable consequence of purposefully 'layering' details pertaining to different sensory modalities (i.e., response propositions; Lang 1979; Calmels et al. 2004), as described within the two preceding stages. Crucially, however, such beneficial effects rely on the performer being a competent user of mental imagery – which should not be assumed from the intervention outset based solely on a high-level skill status – and the stimuli meaningfully resonating with the individual.

In addition, the Five-A Model incorporates several essential psychobehavioural and psychosocial concomitants, some within distinctly dedicated stages. For instance, as a necessary precursor to refining technique, the need for an in-depth analysis is stressed. As such, the 'Analysis stage' explores all necessary routes for improvement to ensure that technical refinement is appropriate, and if so, what aspect of technique requires changing. This stage becomes even more pertinent when considered against evidence showing received wisdom to not necessarily apply at this end of the performance spectrum (Blumenstein et al. 2002; Collins 2002; MacPherson et al. 2013). Such received wisdom might apply in 'general' terms to lesser skilled athletes; however, some prior check is absolutely essential to avoid negative outcomes. Misinterpreting the cause of poor performances when it is not a technical issue can also lead to long-term disadvantages (e.g., poor concentration caused by physical fatigue; Collins et al. 1993), resulting in an almost constant change process since the underlying cause would persist. The Analysis stage also addresses various psychosocial factors such as athlete 'buy in,' confidence, motivation and commitment to the refinement process. The strong and frequent impact of expectancy effects in sport provide a clear demonstration as to why movement changes must be 'sold' to both athletes and coaches. These factors are then reconsidered at each stage by implementing a number of monitoring checks and psychological interventions (e.g., progressive imagery and goal setting), which are appropriate to the stage requirements and supported by our own previous and current research (e.g., Palmer et al. 1999; Holmes and Collins 2001; McClung and Collins 2007; MacPherson et al. 2008).

Finally, a proactive 'Assurance stage' is implemented to increase resistance to the negative effects of competitive pressure; convincing both athlete and coach that the technique no longer requires further tweaking. Essential processes at this stage include increasing levels of self-efficacy under simulated competitive pressure, but also higher-level automation. Once again, effective and optimum employment of expectancy effects is key. Accordingly, the Five-A Model provides both the declarative and procedural knowledge for implementing skill refinement.

Process measures for tracking skill refinement

Having depicted skill refinement as a multifaceted and nonlinear process requiring essential kinematic and control outcomes; it would be useful for coaches and athletes to be able to know whether expected progress was being attained as a result of on-going practice. Indeed, findings from Carson et al. (2013) showed that refinement interventions administered by golf coaches on The European Tour, frequently led to a lack of pressure resistance and regressed back to the original technique; characterised by fluctuations between subconscious and conscious states of control. In practical terms, players and coaches were challenged in knowing when and how much conscious attention should be directed towards the technique. Objectively assessing automaticity presented a greater challenge when compared to the typical two-dimensional video analysis employed to measure technique. Crucially, therefore, the availability of such data would provide coaches with knowledge to better inform their decisions (Abraham and Collins 2011b) when implementing skill refinement.

In an effort to understand the impact of training, many studies have analysed changes to performance outcome (e.g., Perkins-Ceccato et al. 2003; Bell and Hardy 2009). However, Peh et al. (2011) suggested that this measure had been overemphasised within the skill acquisition and performance literature, leading to a lesser understanding of the underlying processes which result in movement developments. Indeed, understanding and evaluating process measures has also been stressed within the sport psychology literature, where they have been termed "effectiveness indicators" (cf. Anderson et al. 2002: 440). For the purposes of tracking skill refinement, effectiveness indicators would need to be sensitive enough to detect nonlinear changes across different levels of system organisation (Newell et al. 2001). Of course, as part of any athlete intervention, self-perceptions can provide useful insight towards issues such as motivation, adherence and the development of imagery scripts. However, there are clear issues relating to report accuracy when assessing changes in automaticity. In some cases, athletes might not be able to accurately convey or understand such a measure, in others, it would be counterproductive for them to do so (i.e., when re-automating the skill). Knowing the former is of vital importance prior to implementing refinement, since this provides a useful indicator of an athlete's mental capacity to be able to change! As such, while we encourage the use of self-report (e.g., as a stimulant for discussion), we now present several objective process measures aimed at informing coach decision making when implementing skill refinement.

Kinematics

The use of two-dimensional video analysis is almost ubiquitous in elite-level applied coaching environments. From this, standardised diagnostic and analytical procedures have typically emerged within sporting domains. Indeed, coaches' understanding of technical effectiveness normally relies on data obtained by this measure. While the use of a video camera is definitely more beneficial than relying on the naked eye, there are, however, noteworthy limitations that should be raised when discussing the optimal tracking of technical refinement.

A video camera will only permit movement to be recorded in a single plane of motion; most usually requiring the presence of a global (environmental) point of reference (e.g., striking object or field target) to conduct an analysis. As such, utilising a global co-ordinate system (GCS) in only one plane of motion prevents a functional understanding of the technique being employed (i.e., what the individual joints or body segments are actually doing), whereby many sporting actions are not limited to a single plane – even when they appear to be (e.g., long jump). Therefore, one major limitation relates to the technical understanding that can be truly gained (cf. Brown et al. 2013). A second limitation arises when longitudinal analyses are required, whereby one cannot guarantee the exact relative repositioning between camera(s) and athlete. Factors associated with perspective error must also be accounted for each time data are collected (Payton 2008). Consequently, this makes inter-session comparisons less reliable since there is a constant need for global reference(s).

While it is more common practice for research to employ three-dimensional analyses of sporting movements, it is not uncommon for analyses to employ GCS (e.g., Myers et al. 2008) and thus, not provide a functional understanding of technique. This is, no doubt, a step in the right direction when compared to two-dimensional video analysis (providing all three planes are considered of course!). However, methods of analysis employed outside of sport could offer a notable improvement. For instance, employing referencing systems based on anatomical segments, termed local (or segment) co-ordinate systems (LCSs), can provide a functional understanding of a joint or body segment of interest (e.g., Panjabi et al. 1974; Grood and Suntay 1983). It is, of course, imperative that the defined LCSs are specific to the refinement being made. Furthermore, advances in anatomical modelling have enabled the possibility to analyse both segment translation (three degrees of freedom) and/or rotation (three degrees of freedom) from these LCSs. However, it is more common to only report three-dimensional kinematics (Paoloni et al. 2010; Selfe et al. 2011). For complex movements where Cardan sequences become problematic to reporting joint rotations (based on current knowledge); we recommend tracking three-dimensional segment translation, since these still offer substantially more than video analysis.

If this method were to be employed in applied sport settings, coaches and athletes would benefit from more detailed information regarding the anatomical motion as a ‘tool’ for both diagnosing and tracking refinement; due to LCSs’ greater emphasis on the movement of segments relative to others (e.g., forearm relative to humerus to calculate elbow angles). From a kinematics perspective, this is clearly what athlete and coach *should be* interested in.

In summary, from a coaching and kinematic perspective, using LCSs provides a more direct measure and functional understanding of the technique being refined. Pragmatically, adopting LCSs is advantageous due to fewer inconsistencies in measurement; data are less affected by variations across trials, days and environments. Consequently, when tracking technical refinement for research purposes, we recommend adopting LCSs as a gold standard measure. For coaches working without such technological capability, using a two-dimensional video camera as a field measure is permissible (although clearly not ideal).

Intra-individual movement variability

With technological advances and integration of concepts from nonlinear dynamics and complexity theory into the domain of motor control, increasing attention and interpretation of the meaning behind intra-individual movement variability (i.e., across trials), its role within system organisation and development has emerged (cf. Davids et al.

2003). Briefly, traditional information-processing theories have interpreted such variance as 'noise' or random fluctuations within the motor system (Schmidt et al. 1979). Whereas, current theory views variability as an important quality of the motor system to overcoming the inherently variable (although usually more subtle in the context of closed and self-paced skills) constraints imposed during movement execution. Accordingly, once skills are learnt to good effect, the demonstrable variability is reduced (although never eliminated) and regarded as *functional* (Davids et al. 2003; Müller and Sternad 2004). Furthermore, the UnControlled Manifold approach (Scholz and Schöner 1999) has been able to deconstruct the structure of this variability into components that are essential to achieving a successful task outcome, termed *performance* variables, and those which are not, *elemental* variables. Performance variables are consistent and provide the motor system with stable solutions; elemental variables on the other hand are less consistent, affording flexibility in response to perturbations. Skilled execution is, therefore, achieved by effectively synergising performance and elemental variables which, in turn, results in the consistent and successful application of a stable solution under changing performance demands (Scholz et al. 2000). Crucially, however, repeated measures of multiple skilled executions should demonstrate a consistent quantity of inter-trial variability for each component part.

Employing the UnControlled Manifold concepts, Carson et al. (2014b) postulated and demonstrated that when a performer decides to make a refinement by consciously allocating greater importance to a single movement component (i.e., Awareness stage), inter-trial variability reduces for that component; whereas, those less-related to the intended change increase in variability. Likewise, MacPherson et al. (2008) found greater consistency across movement components when a holistic rhythm-based cue was employed by an Olympic javelin thrower, versus a specific technical focus showing greater disparity in variability amongst International-level javelin throwers. Accordingly, intra-individual movement variability offers a potential 'psychomechanical' indicator of automaticity during the process of skill refinement. In fact, our most recent longitudinal findings show the emergence, and non-emergence, of this dynamic effect to reflect different levels of success when attempting a refinement in high-level golf (Carson and Collins under review).

Performance outcome variability

Acknowledging the high-level of expertise and financial expense required (at the present moment) to accurately measure intra-individual movement variability, we propose that performance outcome variability could be employed by virtually all coaches as another, more 'low-tech,' measure to track the process of technical refinement. In a study examining gymnastic performances, inter-day competition variability scores across national-classes (sub-junior 6, sub-junior 8, sub-junior 10, junior and senior) and Olympic-level were compared (Bradshaw et al. 2012). Results showed the variability of scores for Olympic gymnasts (0.6–2.9%) to be less than national-classes (0.6–6.5%) across four different apparatus; indicating, therefore, at an inter-group level, performance consistency increases as a function of skill-level. However, an important finding to emerge from these data was the scores for the sub-junior 8 class. Younger gymnasts (~11–12 years) in sub-junior 6 and 8 compete by executing compulsory routines, however, sub-junior 8 gymnasts are permitted to substitute *some* routine elements with their own in order to achieve a higher overall score. Following the sub-junior 8 class, all routines are self-determined. Contrary to the reduction in scoring variability between Olympic and national-classes as homogenous groups, the sub-junior 8 class demonstrated higher variability in scores when compared to the sub-junior 6 class. The authors interpreted this finding to reflect sub-junior 8 gymnasts attempting more difficult routines in order to gain additional points, preparing them for fully self-determined routines at sub-junior 10 and above classes. Therefore, this increase in performance outcome variability could be viewed as a nonlinear transitory stage between two categorical classes (sub-junior 6 and sub-junior 10) when attempting to refine an already well-established set of performance routines. From an applied perspective, this measure would be largely feasible, since performance outcome is normally recorded in many sports (e.g., long jump distance, fairways hit in golf and sprint time in the 200 m). However, we have yet to confirm this trend through empirical research on an individual-basis when attempting a technical refinement. This is something that we intend as part of our on-going research programme in this area.

Tracking caveats

Across all three measures described, there are two important factors that must be considered within applied practice and research. Firstly, for best practice it is imperative to obtain pre-change data as a baseline for comparison. One *potential* problem with this need is that, for some (if not most) performers entering the Analysis stage, the process of change has actually begun. Simply contemplating the possibility of change and becoming aware of what the problem *might* be, already presents the performer in a compromised state, data no longer represent pre-change (i.e., pre-contemplation; Prochaska and DiClemente 1982). Indeed, athletes seeking refinement following relapse from a previous attempt are also unlikely to return to a pre-contemplative state. Rather, it is more likely that athletes will behave in ways close to those contemplating or taking action towards change (Prochaska and DiClemente 1983), such as performing self-re-evaluation and consciousness raising. In some sporting cultures (e.g., golf), we would be very surprised to find a majority of elite-level athletes genuinely in the pre-contemplation stage, since technical refinement has been reported as an almost constant process and feature of training (cf. Carson et al. 2013). Making technical changes in golf has even been reported as a coping strategy *during* experiences of high competitive pressure (Nicholls et al. 2005). Accordingly, this evidence exemplifies the importance of a rigorous Analysis stage and the need for further education in skill refinement amongst athletes and coaches.

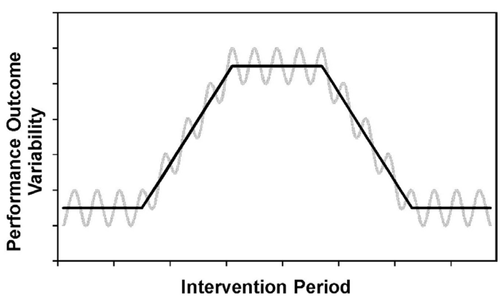

Figure 2. An idealised representation of change in performance outcome variability through the refinement process. Reflecting the inherent nonlinear and potentially noisy nature of the process, the faint line depicts a more representative data set with the straight line representing the trend

Secondly, because applied settings are typically fraught with noise from numerous external sources, data are inevitably going to reflect such disturbances. This is also coupled with the fact that technical refinement needs to be tracked as a longitudinal process; meaning that environmental (e.g., weather) and performer (e.g., mood) conditions are probably not going to remain consistent throughout testing. Accordingly, we urge researchers to sensibly consider the frequency of data collection required for their athlete and skill, with coaching decisions being based on data trends (see Figure 2).

Summary and Conclusion

This review focused on the outcomes that athletes, coaches and researchers should aim for when implementing deliberate technical refinements to already learnt and well-established skills, if they are to be considered effective. Targeting essentials of kinematic change, pressure resistance and long-term permanency, these outcomes reflect changes on different levels and time scales of movement organisation, but which also address the representative challenges faced by elite-level athletes; notably, spatial-temporal characteristics (behaviour) and control mechanisms (Newell et al. 2001). Following, an overview of the Five-A Model was presented (Carson and Collins 2011); a nonlinear and interdisciplinary coaching model designed to facilitate these essential outcomes. Finally, tracking an athlete's progress through this model was addressed using two exemplar measures to indicate an athlete's dynamic level of psychomotor control; intra-individual movement variability and performance outcome variability. While the former has already shown promising results in terms of its application during skill refinement (Carson et al. 2014b), the latter awaits formal validation for such use. In addition, discussion was provided to inform best practice about measures to track the kinematic changes; whereby, six degrees of freedom modelling utilising LCSs was considered the most direct and functionally meaningful method, even if data from three degrees of freedom analyses (i.e., rotation or translation) are reported. Accordingly, we emphasise that evaluative measures should inform coaches' process-oriented decision making when attempting to achieve effective skill refinement.

In conclusion, it is hoped that this review highlights to researchers, coaches and practitioners that the implementation of skill refinement is not the same as skill acquisition or exploiting an athlete's already established levels of automaticity. Therefore, it should not be assumed that literature informing one can be *directly* employed for use during the other. As an applied discipline, we are now starting to understand facilitative processes for skill refinement in greater detail, and factors which contribute to achieving effective (as defined in this review) change (e.g., Collins et al. 1999; Hanin et al. 2002; Carson and Collins 2011; Carson et al. 2013; Carson et al. 2014a; Carson et al. 2014b). Importantly, as evidenced within our existing and on-going research, focus is directed towards the common problems faced by, and requirements of, athletes and their coaches. In turn, high-quality dissemination of research which can offers solutions, has the potential to be most impactful within applied coaching practice. Finally, the conceptualisation of skill refinement as a necessarily complex and interdisciplinary process, affords a wealth of research aimed at understanding how to individually-optimise applied interventions which, if suitably conducted in collaboration with coaching teams, might serve to steer coaches' understanding towards evidence-based and theoretically underpinned practice. In view of the numerous coaching outcomes that exist along the performance pathway (at all levels of participation), such an approach to practitioner development should also permeate to other challenges faced by athletes (e.g., skill acquisition).

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