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FINAL SUBMITTED VERSION

**ORIGINAL ARTICLE**

**Intra-Individual Movement Variability during Skill Transitions: A Useful Marker?**

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26 **Abstract**

27 Applied research suggests athletes and coaches need to be challenged in knowing when and how  
28 much a movement should be consciously attended to. This is exacerbated when the skill is in  
29 transition between two more stable states, such as when an already well learnt skill is being refined.  
30 Using existing theory and research, this paper highlights the potential application of movement  
31 variability as a tool to inform a coach's decision-making process when implementing a systematic  
32 approach to technical refinement. Of particular interest is the structure of co-variability *between*  
33 mechanical degrees-of-freedom (e.g., joints) within the movement system's entirety when undergoing  
34 a skill transition. Exemplar data from golf are presented, demonstrating the link between movement  
35 variability and mental effort as an important feature of automaticity, and thus intervention design  
36 throughout the different stages of refinement. Movement variability was shown to reduce when  
37 mental effort directed towards an individual aspect of the skill was high (target variable). The  
38 opposite pattern was apparent for variables unrelated to the technical refinement. Therefore, two  
39 related indicators, movement variability and mental effort, are offered as a basis through which the  
40 evaluation of automaticity during technical refinements may be made.

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42 **Keywords:** *Technical change, skill modification, skill refinement, conscious control, the Five-A*  
43 *Model, focus of attention*

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**53 Applied coaching: what the field needs**

54 For high-level performers of discrete skills, a crucial and unavoidable requirement is the  
55 ability to execute effective technique under high pressure conditions. As such, two important  
56 factors that must be considered when preparing a performer to compete, are the effectiveness  
57 of current technique, and its level of automaticity which, in turn, leads to resistance against  
58 the negative effects of pressure (Singer, 2002). While addressing the first of these factors  
59 represents a typical practice behaviour amongst high-level coaches, often by means of  
60 kinematic analyses to identify a particular weakness in technique (Bartlett, 2007) and  
61 evaluating performance outcome to understand its effect (Carson, Collins, & MacNamara, in  
62 press), being able to assess movement automaticity presents a far greater challenge.

63 However, if available, such data would be useful for coaches when evaluating the progress of  
64 interventions in the build-up to high pressure situations. This is particularly pertinent, as we  
65 stress throughout this paper, in cases where an already existing and well-established  
66 technique is considered to be in need of *refinement* (cf. Carson & Collins, 2011). In this  
67 regard, Carson and Collins define skill refinement as reflecting “the evolution of technique in  
68 a way that is new to the athlete” (p. 147), therefore indicating the necessity for *transition*  
69 from one original technique to an unfamiliar new version. Although this definition may  
70 initially sound rather drastic, it should be stressed that technical refinement is more often than  
71 not a subtle change or *tweak* to a specific aspect or component of technique. It is not, in  
72 contrast to skill acquisition, a process of *establishing* movement efficiency through  
73 coordination and control (cf. Newell, 1985); these variables having already been well learnt  
74 to good effect. In addition, from a theoretical perspective, such a “tool” could augment our  
75 ability to evaluate different learning and practice environments.

76 Reflecting this important task of refining technique, recent research has highlighted a  
77 significant gap within the literature addressing how a transition from one automated state to

78 another may be achieved most effectively with long-term permanency and resistance to  
79 competitive pressure (Carson & Collins, 2011). This is in stark contrast to either *learning*  
80 new skills, where automaticity is gradually acquired (Hays, Kornell, & Bjork, 2010; Janelle,  
81 Champenoy, Coombes, & Mousseau, 2003), or *performing* skills optimally through  
82 exploiting established automaticity (Beilock & Gonso, 2008; Bell & Hardy, 2009; Mesagno  
83 & Mullane-Grant, 2010), where research is readily apparent. This gap has also been  
84 evidenced empirically within elite coaching practice, revealing unsystematic and inconsistent  
85 approaches employed by European Tour professional golfers and coaches when attempting to  
86 refine technique (Carson et al., in press). Crucially, Carson et al. discovered that  
87 interventions often lead to a lack of pressure resistance as well as regression back to the  
88 original technique, represented by constant fluctuations between automated and de-automated  
89 states, often over a period of several years. In practical terms, players and coaches appeared  
90 to be challenged in knowing when and how much the technique should be consciously  
91 attended to. This challenge was exacerbated when the skill was in transition between two  
92 more stable states, such as when an already well learnt and automated skill was being refined.  
93 Accordingly, golf presents a sound starting point from which to explore the promotion of  
94 effective skill refinement.

95         One potential line of enquiry in identifying the progress of refinement comes from the  
96 study of movement variability, accounting for “the normal variations that occur in motor  
97 performance across multiple repetitions of a task” (Stergiou & Decker, 2011, p. 869).  
98 Previously, movement variability has been considered as the result of measurement “noise”  
99 (e.g., kinematic, kinetic). Notably, however, advances from a nonlinear dynamics  
100 perspective suggest that “it may be that the variance of movement dynamics is as revealing  
101 as, or more revealing than, the invariance in terms of unpacking the nature of the system  
102 organization” (Newell & Slifkin, 1998, p. 157). Consequently, the need for evaluation and

103 critical consideration of movement variability against the factor of automaticity is clear.  
104 Indeed, and relevant to the current paper's focus on golf, recent reviews have focused on such  
105 study as an important route to an enhanced understanding of learning and performance  
106 (Glazier, 2011; Langdown, Bridge, & Li, 2012).

107         Accordingly, in this paper we firstly examine areas of research that have explored the  
108 meaning behind movement and outcome variability as an indicator of skill level. Secondly,  
109 we draw upon the existing applied literature to propose how movement variability may be  
110 indicative of optimal or suboptimal performance states in high-level performers. This will be  
111 examined through a link with attentional focus, thus providing a reasoned prediction and  
112 measure for what could be expected when tracking the skill refinement process. Finally,  
113 exemplar data from golf are provided to show how, as a tool, this may be used to inform the  
114 process of refinement.

#### 115 **Work in other areas: what is on offer?**

##### 116 *Variability as a marker of skill learning*

117 From a process point of view, learning can be characterised as a progression towards  
118 outcome invariance associated with increasing performance-related attainment.  
119 Concurrently, movement variability can also be employed as an indicator of learning or  
120 expertise as movement execution becomes more proficient (Gentile, 1972). However, unlike  
121 the recognised trend towards outcome invariance, the directional change (increased or  
122 decreased) in movement variability has formed the subject of much debate (e.g., Glazier,  
123 2011; Newell & Vaillancourt, 2001). For instance, Bradshaw et al. (2009) found higher  
124 skilled golfers to produce lower variability in key features of the golf swing (e.g., stance and  
125 timing) when compared to lower skilled golfers. In contrast, however, this trend of decreased  
126 movement variability associated with an increase in skill level, appears to be inconsistent  
127 across experimental findings and tasks. For example, Button, MacLeod, Sanders, and

128 Coleman (2003) reported increased movement variability between the elbow and wrist joints  
129 during a basketball free throwing task when comparing experts' to novices' techniques prior  
130 to ball release. Clearly movement variability is a complex phenomenon when analysing the  
131 learning of skills, something that recent theory has attempted to explain.

132 *Resolving the problem of directional change: the uncontrolled manifold (UCM) hypothesis*

133 To better understand this complexity around the significance or meaning of directional  
134 change in movement variability, researchers have focused on one of Bernstein's (1967) most  
135 fundamental questions: that is, how does the motor system organise itself to solve a given  
136 task when a seemingly infinite number of combinations are available to it? Initially,  
137 Bernstein suggested that the central nervous system plans movement by constraining the  
138 many degrees-of-freedom (DoFs) into groups, or synergies, which are pertinent to achieving  
139 the task goal, whilst freezing or eliminating those that are not so essential. Glazier and  
140 Davids (2009) explain the formation of these synergies, as a reflection of lower skilled  
141 performers actively searching for stable (i.e., enduring and difficult to reform) and functional  
142 coordinative states. Therefore, from this perspective, motor planning requires eventually  
143 attending to a small(er) number of functional control variables, providing a simpler  
144 mechanism for movement organisation (Bernstein, 1967). However, in addition to the  
145 contradictory evidence from Button et al. (2003), some authors (e.g., Latash & Anson, 2006)  
146 have argued against this notion, emphasising that freezing out DoFs requires perhaps  
147 enhanced control over certain joints, representing a far from trivial task. This point is a very  
148 important one and something that we shall return to in the next section.

149         Accordingly, if movement planning does not occur through the organisation of  
150 synergies and elimination of the remaining DoFs, what *is* actually happening? Recently,  
151 research has suggested that the answer can be found by considering two different, but equally  
152 important aspects of movement, *stability* and *flexibility*. A synergy is redefined as a

153 structural unit (stability) that is also capable of error correction and adaptation (flexibility).  
154 In comparison to previous thought, the uncontrolled manifold (UCM) hypothesis (Scholz &  
155 Schöner, 1999) seeks to identify motor synergies on the basis that no DoFs are ever frozen or  
156 eliminated but rather, that they are organised in such a way as to provide *both* stability and  
157 flexibility towards achieving specific task goals (Gelfand & Latash, 1998). This is achieved  
158 by constraining (reducing the variability) the DoFs that are important to achieving the task  
159 goal, termed *performance variables*, into a structural unit, while at the same time releasing  
160 (thus increasing the variability) the DoFs that are not as important, termed *elemental*  
161 *variables*. As a result of this, the error–correction mechanism, or flexibility, to implement a  
162 synergy (movement pattern) within a variety of environmental contexts is now enabled.  
163 Accordingly, it is not the directional change of each *individual* DoF that is important but  
164 rather, the structure of co-variability *between* DoFs within the movement system’s entirety  
165 (Langdown et al., 2012; Latash, Scholz, & Schöner, 2002).

#### 166 *Variability as a marker of transitions*

167 Similar to the nonlinear trends described when learning motor skills, recent evidence has  
168 demonstrated the potential for variability in performance results to be a useful indicator when  
169 experiencing a perturbation to an already well-established skill. Following the examination  
170 of successful olfactory and visual search refinement in dogs (i.e., the skill is already learnt, it  
171 simply requires a slight tweak), Helton (2011) concluded that, in order to facilitate long-term  
172 change in the dogs’ ability to detect new stimuli, the existing (already well-established)  
173 detection strategy employed must be “overlaid” with an alternative one, directing attention  
174 towards the to-be-learnt stimuli. Following this, a shift towards consistent detection of the  
175 new stimuli manifested itself as a gradual fading out of the original strategy, representing a  
176 skill phase transition (a sudden and spontaneous shift in system components to form a new  
177 stable behaviour; Kelso, 1984). Data showed performance variability to steadily decrease



178 and stabilise during the acquisition of the original behaviour. This was followed later by  
179 increases during the transitory stage and finally, by reduction back to original levels when re-  
180 stabilisation of the refinement had occurred. On the basis of these results, it seems that such  
181 patterns of change in performance (e.g., the number of fairways hit from tee shots in golf)  
182 could also be employed as a marker by coaches when tracking technical refinement in  
183 athletes.

#### 184 *A summary of available perspectives*

185 The growth of interest in movement variability clearly reflects its potential to significantly  
186 contribute within research of applied coaching practice. However, its interpretation within  
187 the learning context appears to be, at present, very complex and strongly predicted by the  
188 interacting constraints described by Newell (i.e., organismic, task, and environmental; 1986),  
189 thus supporting a trend in favour of intra- as opposed to inter-individual analyses (e.g., Ball &  
190 Best, 2012). Crucially however, in the case of either performance or elemental variables as  
191 described by the UCM, the amount of movement variability demonstrated by performers with  
192 a high level of automaticity should be relatively consistent (intra-individually) and, therefore,  
193 interpreted as entirely functional towards achieving a desired movement goal. Consequently,  
194 one may perhaps characterise the learning process more accurately as a move from  
195 dysfunctional to functional movement variability levels.

#### 196 **Linking theory to practice: variability as a marker for refining already learnt skills**

197 Contrary to the volume of research on learning skills, there has been scarce consideration  
198 towards the expected intra-individual patterns of movement variability when undergoing  
199 transitory stages associated with a consciously initiated perturbation; for example when  
200 attempting a long-term permanent technical refinement once a high-level of skill and  
201 functional movement variability has already been established. However, several recent  
202 studies offer an insight into what can be expected.

203 *Movement variability in applied settings*

204 Addressing the impact of movement variability from the applied literature, MacPherson,  
205 Collins, and Morriss (2008) suggest that when skilled performers exert a heightened level of  
206 conscious control, that is an internal focus (cf. McNevin, Shea, & Wulf, 2003), to a single  
207 aspect of their technique, this results in decreased variability for that aspect, coupled with an  
208 increase in variability associated with other, less related movement constituents. This  
209 dysfunctional movement variability often leads to suboptimal levels of performance. To  
210 contextualise this finding against the UCM paradigm, the aspect subjected to increased  
211 conscious control decreases in variability because perhaps, temporarily at least, it is  
212 considered as more important than other aspects. Indeed, this would support the earlier  
213 contention of Latash and Anson (2006); dismissing the view that eliminating (reduced  
214 movement variability) a DoF represented an easier method of control. In fact, the results from  
215 MacPherson et al. (2008) would suggest the opposite!

216 It is worth addressing at this point somewhat of a contradiction within other  
217 attentional focus literature. In a recent review, Wulf (2013) suggested that an internal focus  
218 of attention served to constrain the motor system (reduce the variability), whereas an external  
219 focus releases the DoFs, therefore promoting functional movement variability that is much  
220 higher. While we support the notion that a specific internal focus would reduce the  
221 variability of that particular component, attention to the co-variability within the movement  
222 system as recommended by the UCM hypothesis appears to be lacking.

223 Accordingly, when applying these concepts relating to the optimum performance of  
224 movement skills to current models of refinement, we suggest that, once a movement has been  
225 learnt, movement variability “settles down” to a reasonably consistent, stable level.  
226 However, when the performer decides to work on a particular aspect of that movement by  
227 exerting increased conscious control, that particular part becomes more consistent (with even

228 lower variability) whilst the variability of other non-associated parts increases. Once the  
229 change is fully re-automated and conscious control has been largely removed, variability  
230 levels return to a consistent and stable level across the different components of the skill (see  
231 Figure 1 for an idealised representation).

### 232 *Ensuring an adequate attentional focus*

233         When attempting to investigate the attentional focus–movement variability  
234 relationship, one important factor to consider is the performer’s ability to apply a sufficient  
235 focus under both automated and de-automated conditions. Previous research into bimanual  
236 coordination suggests that movement of the upper-limbs are tightly coupled, with the brain  
237 deploying signals to the same muscle structures across both limbs as a default (Kelso,  
238 Southard, & Goodman, 1979). Accordingly, symmetrical coordination of the limbs, known  
239 as in-phase, requires identical firing of muscle groups and reliably produces the most stable,  
240 automatic mode of coordination (Kelso, 1984; Zanone & Kelso, 1992). In contrast,  
241 movements following an anti-phase pattern, alternated activation of the same muscle groups  
242 of each limb, are slightly less stable and require an increased attentional focus in order to  
243 stabilise (Temprado, Zanone, Monno, & Laurent, 1999). The implications of these findings  
244 within the context of sports coaching is that changing, or disrupting, an already stabilised  
245 coordination pattern (consider this to represent an in-phase pattern) will be most effective if  
246 there is an attempt to de-couple the existing relationship between the left and right upper-  
247 limbs, should that be the desired modification. In other words, it is possible to apply a greater  
248 intensity of internal focus on one of the limbs in isolation rather than attending to both limbs  
249 simultaneously. As a result, this will likely serve to de-automate/destabilise the coordinative  
250 structure across the limbs via interference to the existing neural pathway. Therefore, this  
251 provides a theoretical and empirical basis on which to investigate the attentional focus–  
252 movement variability relationship.

253 To exemplify how tracking trends in such a process may be utilised within the applied  
254 setting, we now provide a brief account of some pilot work in high-level golf examining the  
255 effect of attentional focus on movement co-variability. Based on the arguments presented  
256 above, we hypothesised that, when compared to the variability patterns observed in a well-  
257 known and automated skill, increased (conscious) attention to a particular part of the skill  
258 would result in a decrease in variability. By contrast, and as another feature of this attention,  
259 the variability of non-crucial (i.e., not attended to) components would result in increased  
260 variability.

### 261 **What we might expect: exemplar cases of acute technical refinement in golf**

#### 262 *Methods*

263 *Participants.* Three right handed male golfers between the ages of 25 and 30 years ( $M =$   
264  $26.7$ ,  $SD = 2.9$ ) were recruited for this study. All were members of the Professional Golfers'  
265 Association (PGA) of Great Britain and Ireland. Preceding data collection, participants were  
266 required to read an information sheet and provide signed formal consent. Ethical approval  
267 was gained from the University's Ethics Committee prior to data collection.

268 *Procedures.* Prior to testing, participants were asked about their "natural" golf swing  
269 technique. It was established that two participants preferred to shape the golf ball in a left-to-  
270 right direction (fade) and the remaining participant a right-to-left direction (draw) during  
271 play. All confirmed that to execute their natural technique would require a low level of  
272 conscious control; in other words, they could perform that particular type of shot with a high  
273 level of automaticity. After a warm-up phase of approximately five minutes, participants  
274 completed 10 full golf swings adopting their natural technique. To help promote  
275 automaticity, shots were executed with a commonly used golf club, a 7 iron, which was  
276 reported as easy to perform successfully, towards a distant target in a straight line. Prompts  
277 were provided after Trials 3, 6, and 9, to focus on hitting the target. Following these trials,

278 participants discussed the changes in technique required to execute the non-preferred type of  
279 shot (i.e., fade when a draw was preferred, or vice versa); kinaesthetic cues were developed  
280 by each participant to help them detect the difference between the two techniques. Emphasis  
281 was placed on developing one key unilateral thought to focus on (a target variable) in order to  
282 bring about the desired change (cf. Kelso et al., 1979). As a result, all reported a focus  
283 towards the right arm movement during the backswing. Ten shots were then executed as per  
284 the previous condition, only this time participants were asked, and reminded after Trials 3, 6,  
285 and 9, to remain focused on their developed cue. Immediately following each of the two  
286 conditions, participants were asked to rate their overall level of mental effort (representative  
287 of conscious control) exerted during shot executions using the Rating Scale for Mental Effort  
288 (Zijlstra, 1993). The scale ranged from 0 (*not at all effortful*), to 75 (*moderately effortful*),  
289 and 150 (*very effortful*). For the second condition, this reflected the level of awareness  
290 directed towards the kinaesthetic cue aimed at changing the target variable. All kinematic  
291 data were collected using an inertial-sensor motion capture suit (MVN Biomech Suit, Xsens<sup>®</sup>  
292 Technologies B.V., Enschede, The Netherlands) at a sampling rate of 120 Hz.

293 *Data processing and analysis.* Raw data from the MVN Studio Software (Xsens<sup>®</sup>  
294 Technologies B.V, Enschede, the Netherlands) were exported into c3d file format and  
295 analysed using six degrees of freedom modelling with Visual3D<sup>™</sup> v4.89.0 software (C-  
296 Motion<sup>®</sup> Inc, Germantown, MD, USA). Two swing events were identified to define the  
297 backswing, with the time between each event normalised to 101 points. The first event  
298 (onset) was defined as the frame when the left hand's centre of gravity linear speed crossed a  
299 threshold value of 0.2 m/s in the local medial/lateral axis relative to pelvis. The second event  
300 (top of swing) was defined as the frame when the distal end position of the right hand reached  
301 its maximum value in the global vertical axis. All data were exported to Microsoft Excel<sup>®</sup>  
302 2010 for graphical analysis of variables related to the right and *left* upper-limbs.

303           Of particular interest was the variance/covariance interaction between body segments  
304 that were related (i.e., the right upper-limb; target variable) and unrelated (i.e., the left upper-  
305 limb; a non-target variable) to the technical refinement.

### 306 *Results*

307 Mental effort ratings increased for all participants between the initial target focus (low mental  
308 effort) and second unilateral internal focus (high mental effort) conditions; results are  
309 presented in Figure 2. Movement variability showed a *decrease* in the right elbow for all  
310 participants during the high mental effort condition, where there was an explicit focus on the  
311 kinaesthesia of the right arm (see Figure 3 left column). In association with directing  
312 attention to this unilateral movement constituent, and as predicted, movement variability  
313 *increased* for left upper-limb joints (see Figure 3 right column). Changes in kinematic joint  
314 angles are presented in Figure 4, evidencing that changes intended in the second condition  
315 were actually achieved. One distinct feature of these graphs is the inter-individual nature of  
316 change for both variability and kinematic measures. As such, statistical treatment of data was  
317 seen as inappropriate.

### 318 *Discussion*

319 These exemplar cases aimed to examine the implementation of intra-individual movement  
320 variability when addressing technical refinement against a factor of conscious control within  
321 a single session. In doing so, kinematic analyses provide insightful data to support the  
322 suggested patterns of movement variability during this transitory process, especially when  
323 considered against the theoretical suggestions of the UCM hypothesis (cf. Scholz & Schöner,  
324 1999). What is important to highlight at this early stage of experimentation, is our intention  
325 not to provide a test of the UCM hypothesis, but rather to use its insights into movement  
326 planning and organisation to help interpret our data and guide applied practice. In addition,  
327 the data support previous findings that show a decrease in movement variability when an

328 internal focus is applied (cf. Wulf, 2013). Furthermore, they reveal that the structure of  
329 variability across related and unrelated variables is highly complex, supporting the need for  
330 intra-individual analyses, but which can indeed inform about the nature of the motor system's  
331 organisation (Newell & Slifkin, 1998).

332         Data support the underlying importance of tracking kinematic factors to determine a  
333 stable level of execution or level of automaticity for complex movements (MacPherson et al.,  
334 2008), and could also be viewed as support towards the progression of events across the  
335 attractor landscape over multiple time scales, as described by Newell, Liu, and Mayer-Kress  
336 (2001). This is a crucial point within coaching practice since describing the motor system at  
337 a behavioural level (i.e., analysis of technique) will not provide any indication towards the  
338 level of automaticity or stability within the system evolving over the course of such a  
339 dynamic transitory process. Hence, as mentioned within the introduction, being able to  
340 assess both factors of execution remains essential when assessing the refinement of skills,  
341 since one would demonstrate the actual execution of correct technique (location along the  
342 attractor landscape) before it was able to be performed with high levels of automaticity (depth  
343 of the attractor well). Indeed, analysis of performance (cf. Helton, 2011) may also prove to  
344 reveal a longer-term timescale for refinement at an outcome level. In short, it is unrealistic to  
345 expect long-term pressure resistant technical change to result from a single session of  
346 practice.

347         From a practical point of view, by measuring movement variability against mental  
348 effort, two process markers are provided, enabling greater triangulation (along with  
349 conventional outcome data) of information which, in turn, can be used to better inform  
350 coaching decisions and, from a research perspective, track change under different practice  
351 conditions.

352           One limitation of the data presented is the lack of detailed consideration towards the  
353 co-variation between several joints across a coordinative structure (e.g., multiple joints of the  
354 same limb), nor between axes of rotation relating to each of the target and non-target  
355 variables. An analysis of co-variability across proximal-to-distal joint couplings may prove  
356 additionally insightful, especially when adopting a focus that is either more proximal (e.g.,  
357 the left elbow) or distal (e.g., the left wrist) to the movement's centre. Indeed, this is  
358 something that future research should investigate. However, in the case of highly asymmetric  
359 movements such as the golf swing, assessing the co-variability between joints across both  
360 limbs (i.e., flexion-extension, internal-external rotation, and add-abduction of the left and  
361 right elbows for instance) may not prove as useful since it may not be possible, or even the  
362 desired technical refinement, to individually constrain the axes of rotation about a joint as a  
363 direct function of attentional focus. Nor will the corresponding axes of rotation about  
364 opposing joints (e.g., left and right elbows) necessarily be coupled when performing the golf  
365 swing. However, this may be of interest when examining in-phase movements typical of  
366 laboratory experiments (e.g., Zanone & Kelso, 1992). What these data do support is the  
367 potential use of movement variability directed towards the general area, but that is locked  
368 into the performer's focus of attention. Therefore, from a coaching perspective, providing  
369 each variable, target and non-target, remain on the course of variability pattern as depicted in  
370 Figure 1; both would present appropriate markers for tracking the skill refinement process.

371           In viewing the significant and robust contribution that may be gained from employing  
372 an analysis using the UCM method, this study is limited by not doing so; however, is  
373 something that experimenters may wish to consider. Indeed, our own future work will aim to  
374 include some elements of this testing in representative performance environments.  
375 Principally, there were several reasons to explain its exclusion from the present study. We  
376 were not able to conclusively identify success in achieving a predetermined position of the



377 target variable. Rather, this was related to the performer's ability to reproduce the self-  
378 generated kinaesthesia. When conducting an analysis using the Uncontrolled Manifold  
379 method, Scholz, Schöner, and Latash (2000) state that mixing successful and unsuccessful  
380 trials would not make sense since they correspond to different manifolds. With the  
381 possibility for this mixture within our data, we considered such an analysis as potentially  
382 flawed. The authors also later explain that to perform such an analysis would require  
383 sufficiently more trials than we have collected, namely ~20 (Latash, Levin, Scholz, &  
384 Schöner, 2010). Accordingly, and in contrast to the methods reported in this study, greater  
385 efforts would need to be focused on predefining a task variable (e.g., golf club position or  
386 exact positioning of a target variable) to be able to compare between successful and  
387 unsuccessful trials. This would therefore facilitate an analysis of different hypotheses to  
388 determine which variables were considered to provide stability or flexibility to the technique.  
389 To obtain a detailed examination of this method in a comparable scenario, pistol shooting, we  
390 encourage those interested to read the paper by Scholz et al. (2000) who compared the impact  
391 of different variables on shooting success. What we hope to have achieved in this paper is to  
392 establish a formal link between the structure of a movement synergy and the intensity and  
393 direction of a performer's attentional focus (conscious control/automaticity).

#### 394 **Conclusion**

395 By adopting the theoretical standpoint offered by the UCM hypothesis, it is clear that  
396 attention in measurement must be paid towards the structure of movement variability or, in  
397 other words, the co-variability across different components of a skill when addressing  
398 technical refinement. In using this approach, an examination into the effects of associated  
399 attentional foci on movement kinematics during the process of refinement has been made.  
400 Therefore, when movement variability and mental effort are measured in tandem, a coach,  
401 most probably through assistance from applied sport science support (cf. Carson et al., in

402 press), may be better informed about a performer's level of automaticity and readiness to  
403 compete. What is now required to verify these contentions and initial findings is to  
404 implement and assess the practical use of movement variability over an extended time period  
405 within an applied coaching framework, and across a variety of changes and performers when  
406 undergoing a planned technical refinement. In doing so, this may provide more robust  
407 evidence towards the theoretical meaning and operational use of movement variability. In  
408 sum, this paper highlights the need for an understanding of movement variability as an index  
409 of attentional focus when implementing technical refinements in applied coaching practice.

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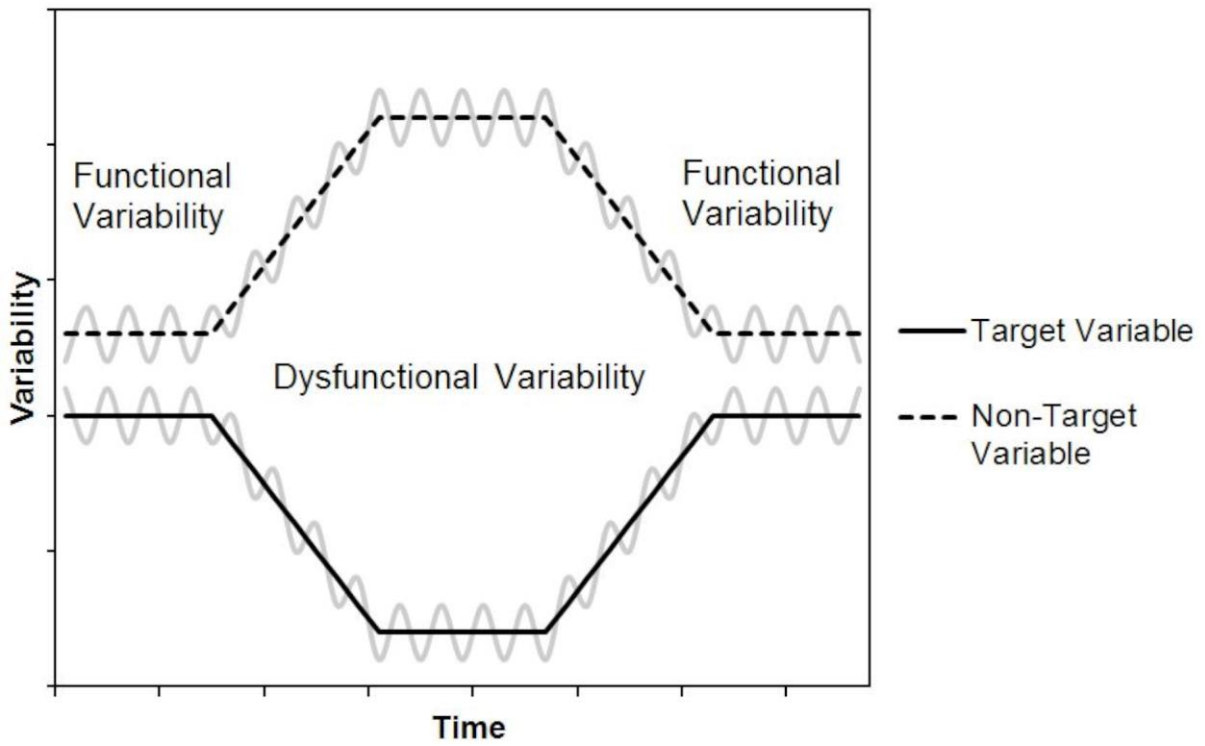
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510 Figure 1.

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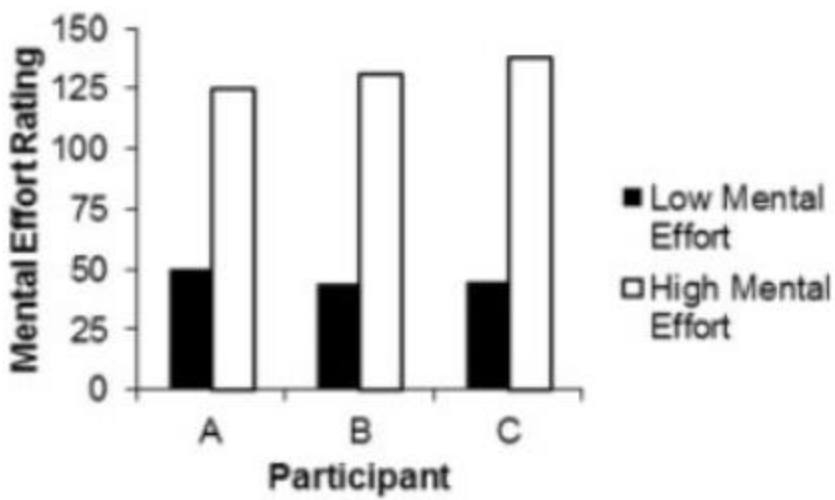
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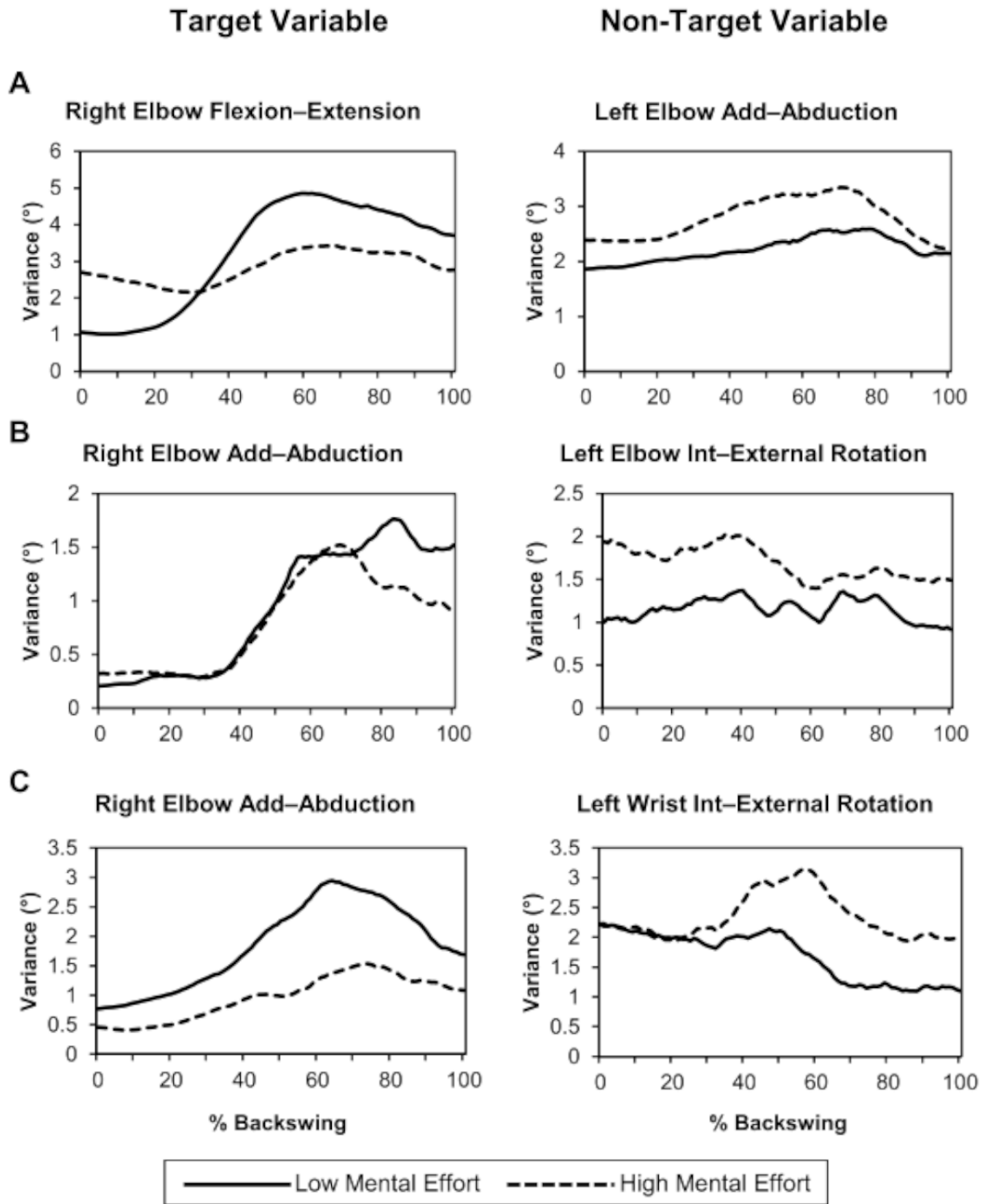
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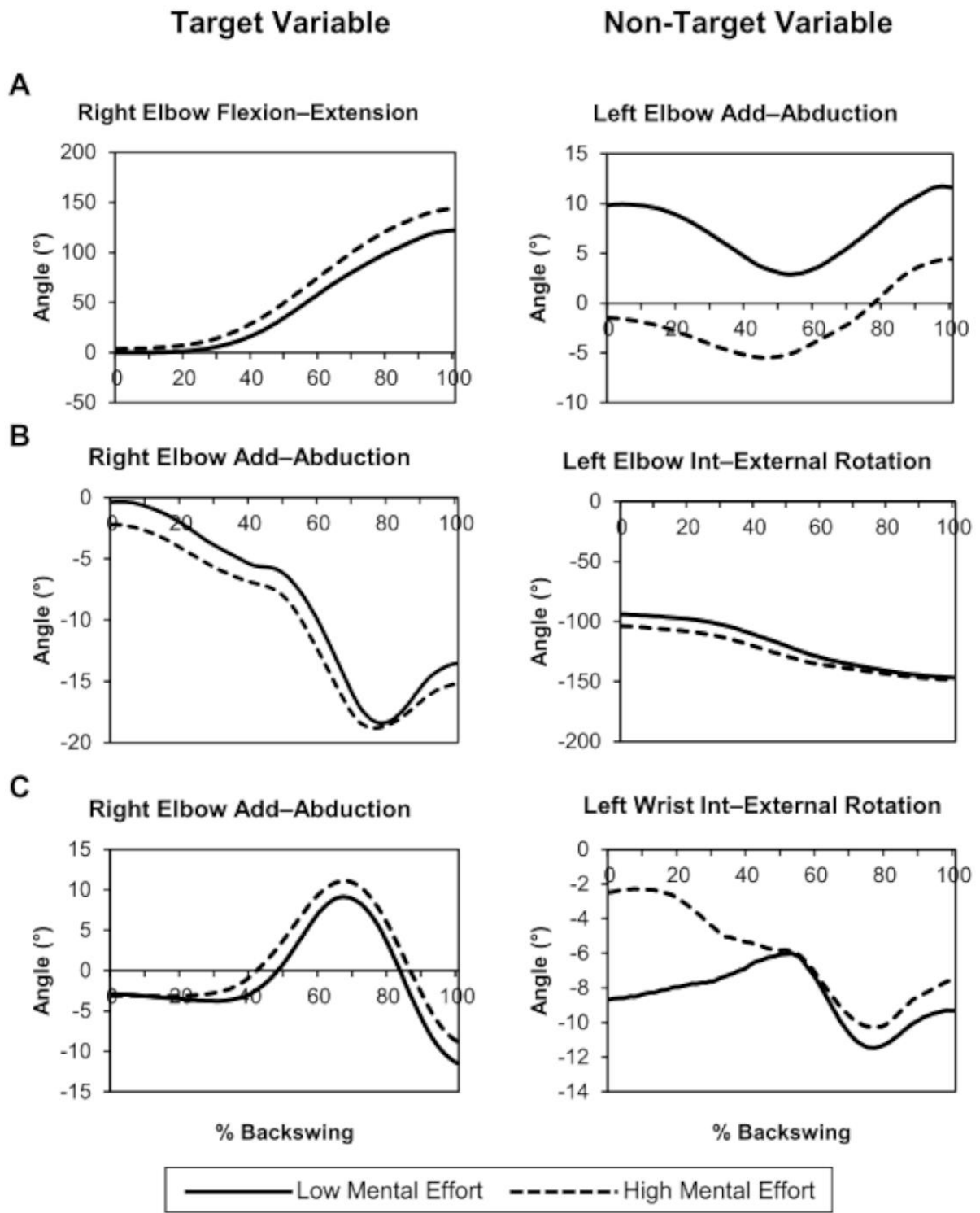
520 Figure 2.



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522 Figure 3.





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524 Figure 4.

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528 **Figure captions**

- 529 • Figure 1. An idealised representation of co-variability through the refinement  
530 process, depicting initially stable and consistent levels of variability for two components of a  
531 movement (functional variability). As one of those components is consciously attended to  
532 (target variable), movement variability decreases for that component associated with an  
533 increase in variability for the non-targeted component (dysfunctional variability). Due to the  
534 levels of dysfunctional movement variability being inherently unknown within each  
535 individual, completion of this phase is characterised by a levelling out in variability,  
536 signifying maximum de-automation. Gradual automation of the new technique is shown to  
537 occur through a stable return to largely subconscious thought and functional variability of  
538 both movement components. Reflecting the inherent nonlinear nature of this process, the  
539 faint lines depict a more representative data set with the straight lines representing trends.
- 540 • Figure 2. Mental effort scores when performing under initially low and then high  
541 levels of mental effort directed towards a target variable.
- 542 • Figure 3. Movement co-variance for kinematics subjected to an increase in conscious  
543 control relating to the right limb (target variable) and less associated variables relating to the  
544 left limb (non-target variable), measured from the swing onset to the top of the backswing.
- 545 • Figure 4. Mean positional data for the target and non-target variables measured from  
546 the swing onset to the top of the backswing.

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