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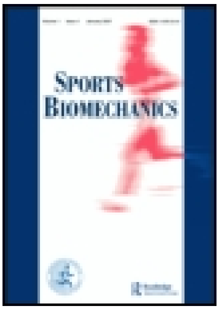

Sports Biomechanics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rspb20

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Published online: 07 Feb 2014.

To cite this article: Marius Sommer, Charlotte Häger & Louise Rönnqvist , Sports Biomechanics (2014): Synchronized metronome training induces changes in the kinematic properties of the golf swing, Sports Biomechanics, DOI: 10.1080/14763141.2013.873817

To link to this article: http://dx.doi.org/10.1080/14763141.2013.873817

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Sports Biomechanics, 2014
http://dx.doi.org/10.1080/14763141.2013.873817

Synchronized metronome training induces changes in the kinematic properties of the golf swing

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(*Received 18 April 2013; accepted 4 December 2013*)

Abstract

The purpose of this study was to evaluate possible effects of synchronized metronome training (SMT) on movement dynamics during golf-swing performance, as captured by kinematic analysis. A one-group, between-test design was applied on 13 male golfers (27.5 ± 4.6 years old, 12.7 ± 4.9 handicap) who completed 12 sessions of SMT over a four-week period. Pre- and post-assessments of golf swings with three different clubs (4-iron, 7-iron, and pitching wedge) were performed using a three-dimensional motion capture system. Club velocity at three different swing phases (backswing, downswing, and follow-through) was measured and cross-correlation analysis of time-series signals were made on joint couplings (wrist–elbow–shoulder) of both arms, and between joints and the club, during the full golf swing. There were significantly higher cross-correlations between joint-couplings and concomitant changes of the associated phase-shift differences, as well as reduced phase-shift variability at post-test. No significant effect of SMT was found for the club velocities. We suggest that domain-general influences of SMT on the underlying brain-based motor control strategies lead to a more coordinated movement pattern of the golf-swing performance, which may explain previous observations of significantly improved golf-shot accuracy and decreased variability after SMT.

Keywords: *Timing training, coordination, movement dynamics, joint couplings, cross-correlation analysis*

Introduction

To increase and sustain functional performance, whether defined as the pursuit of athletic excellence in high-precision sports as, for instance, in golf or associated to activity limitations due to impairments, the execution of purposeful motor tasks requires timing and coordination. As suggested by Buonomano and Laje (2010), timing refers to the production of intrinsically timed motor actions, involving complex spatiotemporal patterns of muscle activation. The importance of motor timing in the generation of coordinated motor actions has been emphasized repeatedly (e.g. Ivry, 1996; Mauk & Ruiz, 1992; Medina, Carey, & Lisberger, 2005; Meegan, Aslin, & Jacobs, 2000), and as coordination includes and specifies the spatiotemporal ordering between component parts (e.g. Jantzen, Oullier, & Kelso, 2008), precise timing between individual body/limb segments in complex, multi-joint tasks such as the golf swing seems especially crucial.

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In golf, timing is one of the central attributes that professional players (e.g. Nicklaus, 1974; Watson, 2011), instructors (e.g. Pelz & Frank, 1999), and scientists (e.g. Neal, Lumsden, Holland, & Mason, 2008) believe to be important for optimal swing performance and subsequent golf-shot accuracy. Accordingly, swing tempo and swing rhythm (e.g. Grober & Cholewicki, 2008; Jagacinski, Kim, & Lavender, 2009; Kim, Jagacinski, & Lavender, 2011), along with timing configurations of arm and body segments (e.g. Neal et al., 2008; Nesbit & Serrano, 2005; Springings & Neal, 2000; Zheng, Barrentine, Fleisig, & Andrews, 2008a, 2008b), have typically been investigated. There, however, is no clear consensus in regard to how this timing is achieved, or if and how specific timing training may influence the golf-swing performance.

In agreement with the findings of Libkuman, Otani, and Steger (2002), Sommer and Rönnqvist (2009) have recently provided evidence that improved motor timing following synchronized metronome training (SMT) may lead to positive effects on golf performance by means of a significant increase in outcome accuracy combined with a decrease in outcome variability, measured by the distance of the golf ball from the pin and how it varied. The SMT was carried out using the Interactive Metronome® system (Interactive Metronome [IM], Sunrise, FL, USA), which is a goal-oriented intervention program that aims to facilitate the improvement of an individual's rhythm and timing (Interactive Metronome®, IM, Orlando, FL, http://www.interactivemetronome.com) (for further details, see Methods section).

In line with the aim of SMT, it has been theorized that rhythmic cuing and rhythmic auditory stimulation 'appears to enhance motor control in rehabilitation by facilitating planning and execution through a strong entrainment and synchronization effect of repetitive rhythmic sensory signals on the motor system' (Malcolm, Massie, & Thaut, 2009, p. 71). The authors argue that the auditory system, during rhythmic/timing training, builds time traces that serve as a spatiotemporal motor template onto which movements later can be mapped. Positive effects of SMT have also been described by means of improved cognitive and motor functions as well as controlled attention and academic skills in school children and improved gait pattern in hemiparetic post-stroke patients (McGrew, 2013; Taub, McGrew, & Keith 2007), smoother and shorter arm movement trajectories in children diagnosed with spastic hemiplegia (Johansson, Domellöf, & Rönnqvist, 2012), and improved aspects of motor control in different clinical populations (Bartscherer & Dole, 2005; Cosper, Lee, Peters, & Bishop 2009). While several mechanisms may elucidate these findings, one might be that there are structural aspects of timing that generalize across different sequential movements of various complexities.

Although the movement trajectory and movement timing of individual body segments are suggested to influence the club head trajectory and subsequently the golf-shot outcome (e.g. Horan, Evens, & Kavanagh, 2011; Nesbit & McGinnis, 2009), the effects of intra-segmental joint coupling, timing, variability, and movement dynamics throughout the golf swing are not well understood. However, recent studies examining the inter-segment coupling between continuous time-series signals of head and thorax, and thorax and pelvis (Horan & Kavanagh, 2012), and between and within pelvis and upper torso (Beak et al., 2013) during the golf downswing show promising results in regard to revealing the underlying movement dynamics by means of cross-correlation analysis.

Thus, the objective of this study was to evaluate whether extensive SMT may induce changes in the kinematic properties of the golf swing. Accordingly, timing relationships within each arm and in relation to the club velocity profiles were analysed by means of time-series signals gained from calculations of cross-correlation between different joint motion linkages. Furthermore, the phase shift (zero-lagging) of each joint-pair was assessed to map any changes in the temporal sequencing of the golf swing as a result of SMT. We hypothesized that between arm-joints motion would become more synchronized and better coordinated in terms of higher cross-correlations as an effect of increased motor timing from SMT, and that the variability of the limb inter-joint couplings would decrease. Moreover, as the stability of the coordination pattern is reflected by the coordination variability (Hamill, van Emmerik, Heiderscheit, & Li, 1999), we hypothesized that the spatiotemporal properties of the golf swing would become more coordinated—manifested through less variance and with decreasing phase shifts between joint couplings—as an effect of SMT.

Methods

Participants

Thirteen right-handed male golfers (*M*± *SD*; height: 180 ± 4 cm, mass: 77 ± 11 kg) participated. They had 10.9 ± 5.0 years of golf-playing experience, and their age and mean golf handicap ranged from 20.0 to 33.7 years (27.5 ± 4.6 years) and 5.0 to 19.5 handicap (12.7 ± 4.9). The experiment protocol was explained to the participants who provided informed consent prior to testing, all in accordance with the ethical standards of the Helsinki Declaration. The kinematic pre–post golf-swing data analysed in the present paper were extracted from golf performance made by golfers included in the SMT experimental group that participated in a previous study (Sommer & Rönnqvist, 2009) investigating the effect of SMT on golf-shot accuracy outcomes.

Apparatus

Pre- and post-test golf performance was established in a golf simulator (P3 Pro Golf Simulator®, Sport Vision Technologies, Bethel, PR, USA, http://www.p3proswing.com) located in a 5 m×5 m × 3.5 m golf laboratory. For each golf shot, the swing performance in terms of three-dimensional (3D) kinematic data was measured with an optoelectronic motion capture system (ProReflex, Qualisys AB, Gothenburg, Sweden, http://www.qualisys.com) consisting of four cameras (240 Hz) placed around the golfer who performed the golf shots (Figure 1(a)).

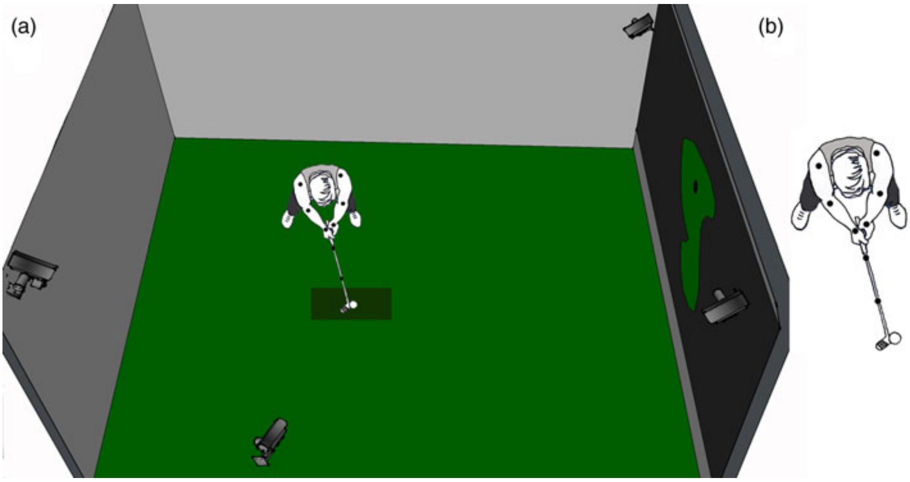

Figure 1. Experimental set-up (a) and positions of the reflective markers (b) on respective right and left shoulder, elbow, wrist, and on the golf club by respective club top marker, and the club base marker.

All trials were performed with participants' own clubs, and the ball was shot from a 22.9 cm×35.6 cm sensing platform covered with 1.5 cm high artificial grass. The participants typically executed a full swing and hit a real golf ball that would travel approximately 3 m before hitting a screen. The screen displayed the fairway, on which the ball was positioned, as well as the green and the hole with a pin and a flag. The golfers were instructed to aim for the pin. A visual ball path trajectory line of the golf ball's flight to the final position was instantly projected on the screen as the player made his shot.

The IM® system assessed participants' timing and rhythmic skills at pre- and post-test and also the training intervention was utilized (see Sommer & Rönnqvist, 2009). The IM is a computer program for Windows based on the traditional music metronome which is used in order to improve and maintain timing and rhythmicity. It was set up with standard stereo headphones and a set of contact-sensing triggers, including a hand glove and a flat plastic footpad. The participants were requested to perform uni- and bilateral, rhythmic hand/arm and leg/foot movements in conjunction with a computer-generated reference beat, heard through headphones. The IM system generated scores on two dependent measures: namely the mean millisecond discrepancy between participant's responses and the reference beat (timing skills), and the inter-response time that was a measure of how close each hit was timed to the previous hit (rhythmic skills). A high score reflected a larger discrepancy in milliseconds between the metronome beat and participant's movements, i.e. a score that indicated less accurate timing. Thus, lower timing scores indicated more accurate timing.

Procedures

At the time of the golf pre-test, the participants began with setting the distance from the ball (fairway) to the pin. It was emphasized that they should choose a distance from the pin that was, with some margin, within the reach of their shot with each club (4-iron, 7-iron, and pitching wedge, respectively). Before the pre- and post-test measurements started, they could try up to five practice shots with each club to familiarize themselves to the new surface and the artificial environment. At the start of each measurement, the participants were instructed to aim for the pin and to proceed at their own pace. All golfers performed 10 shots with each club in a counterbalanced randomized block design. Identical procedures were used for the pre- and post-tests. The golfers included did not play any golf or performed any golf-related activity during the 4 weeks of SMT.

The SMT intervention

The SMT intervention included 12 sessions of training with the IM system, distributed over three 45–50 min sessions a week during a 4-week period after the pre-test. During training sessions, the IM system instantaneously transposed the timing information into discriminative, temporally based guide sounds presented in the participant's headphones, continually indicating whether the response was *on target*, *early*, or *late*. A contact that matched the beat within ± 15 ms generated a high pitched tone in the centre of the headphones which was simultaneously perceived in both ears. An early contact that preceded the beat by more than 151 ms or by 150–16 ms generated a *very low* or *low* pitch tone in the user's left ear, respectively. A late or very late contact (a contact that follows the beat) generated similar pitch tones in the right ear. These instantaneous guide sounds enabled participants to deliberately correct their timing errors as they occurred. Guide sounds were not delivered during pre- and post-test.

During each of the first seven sessions, participants performed 4–10 successive exercises involving basic uni- and bi-lateral motor tasks such as clapping both hands together, tapping one hand alone against the thigh, alternating toe taps on the footpad, tapping one toe or heel alone on the footpad, alternating between tapping one hand on the thigh and one toe on the footpad, and balancing on one foot while tapping with the toe on the contralateral footpad. Each exercise typically lasted from 2 to 10 min, with the metronome reference beat set to 54 bmp. From session number 8, some new reference beat tempos (45, 66, and 78 bmp) and tasks were introduced (i.e. clapping hands while standing on a balance-board, hitting wall mounted sensors with hands crossing body midline, clapping hands behind back, and tapping footpad crossing body midline), however, with similar exercise durations and amount of exercises performed. At the completion of intervention, participants had engaged in approximately 27,000 motor repetitions. None of the exercises performed mimicked body movements involved in a golf swing.

Recording and data collection

The motion capture system provided real-time position (*XYZ*-coordinates; Figure 2(a)) and orientation data of markers attached on anatomical landmarks on the body of the participants. The cameras were linearized and the system was calibrated (before start of each golf measurement session/participant) according to manufacturer's instructions until the 3D residuals for all cameras became less than 1.0 mm, and the procedure was repeated before each data collection session.

A total of six spherical reflective markers with flat fundament were fixated with skin-friendly adhesive tape to the left and right shoulders (diameter = 24.5 mm), elbows (diameter = 24.5 mm), and wrists (diameter = 12.4 mm) of the golfer. In addition, two markers were placed on the clubs by means of a 20 mm wide reflective tape (Scotch 3M) around the club shaft at the top of the shaft where it met the base of the handle (club top marker), and at a point at 170 mm below the top marker on the shaft (club base marker) (Figure 1(b)).

Data extraction and analysis of the kinematic properties

At pre- and post-test, the first 15 and the last 15 of the 60 shots performed by each participant were recorded. Thus, a total of 10 shots per club and test for each golfer were documented. Each sequence started at the first observed motion of the club head during the backswing (with a pre-trigger time of 1 s) and was terminated at the end of the follow-through phase (Figure 2(a),(b)). The kinematic data from the golf-swing movement from each camera were first transformed into 3D (x, y, and z) coordinates by the system software (Qualisys Track Manager 2.7) and then analysed offline in MATLAB 8.2 (The Mathworks Inc., Boston, MA, USA). The total number of successful kinematic recordings was 382 for the pre-test condition and 376 for the pre-test condition. A total of 22 kinematic recordings had to be excluded due to poor recording quality (e.g. if a marker was missing and/or occluded and only part of the movement could be captured). Data were smoothed using a second-order 12-Hz dual-pass Butterworth filter. For each successfully recorded golf trial, the onset, ball impact, and offset of the golf-swing movement were first identified from the 3D movement trajectory and the velocity profile of the marker at the club base. Onset of the backswing was defined as the frame at which club base marker exceeded a velocity limit of 50 mm/s and increased over the next five frames and, in addition, displaced more than 5 cm in the horizontal direction (negative x-axis; Figure 2(a)). The time of the ball impact was

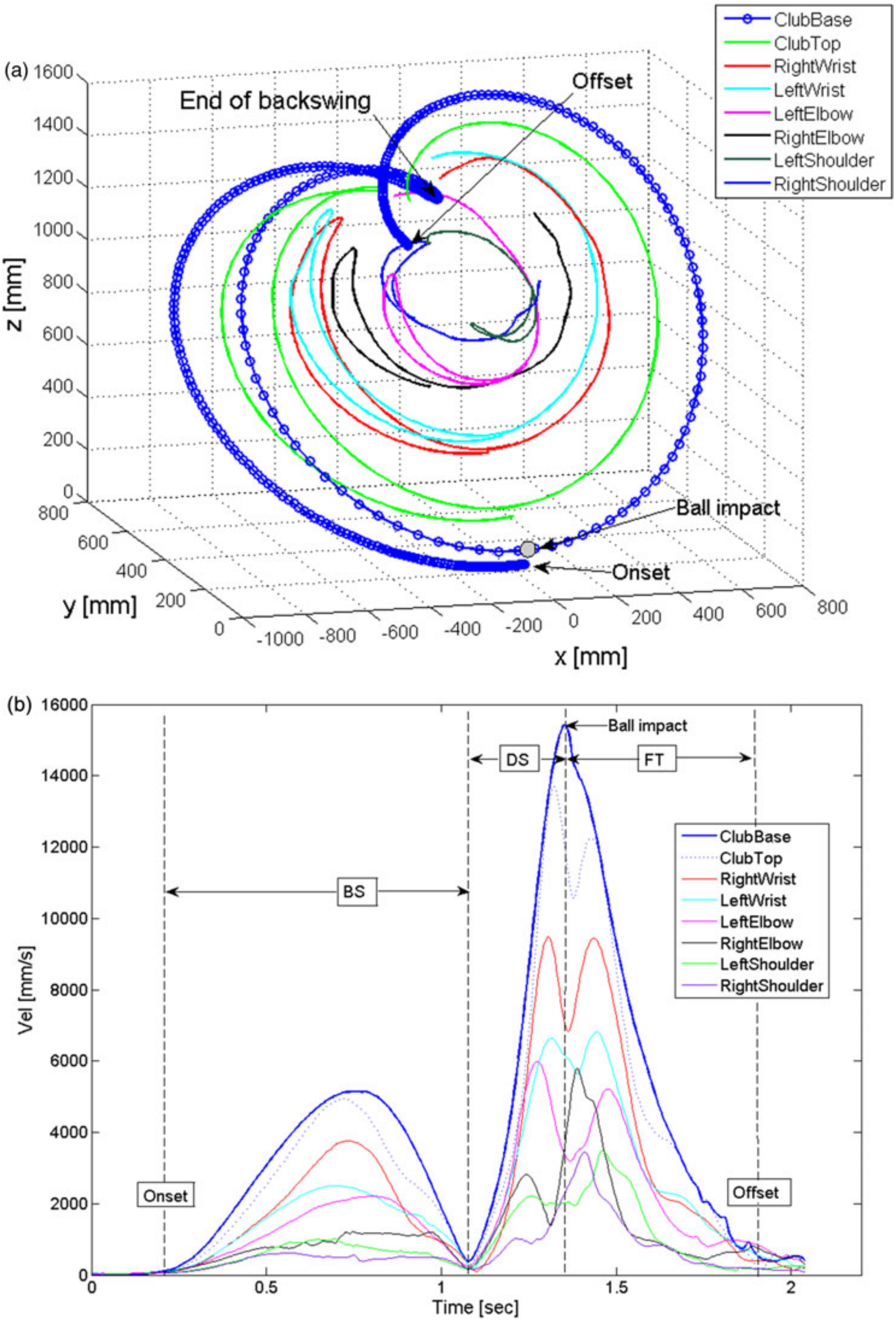

Figure 2. (a) Illustration of 3D profiles of club base, club top, the right and left wrist, elbow and shoulder movement trajectories and (b) corresponding velocity profiles plotted for respective marker for a typical golf swing from onset to offset. BS, backswing phase; DS, downswing phase; FT, follow-through phase.

defined as the time when the maximum peak speed of the downswing movement was interrupted (at the first identified frame at ball impact) due to club head-ball impact. The offset was defined at the end of the whole golf swing (i.e. end of the follow-through motion), at the time limit when the club base marker velocity became less than 5 mm/s (Figure 2(a),(b)).

Velocity (resultant) outcomes generated from the club base marker were peak velocity backswing, velocity at the end of the backswing, and velocity at ball impact. Also, intra-joint coordination in terms of cross-correlations and corresponding phase shifts deliberated from the velocity profiles during the golf-swing motion was calculated. To gain insight into the intrinsic dynamics and timing of the golf-swing performance and training-related differences (effect of SMT) between pre- and post-test, the intra-joint coordination between the elbow–wrist, shoulder–elbow, and shoulder–wrist joints of each arm, and in addition, between the club base marker and the shoulders (right and left, respectively), and between club base and the wrists (right and left, respectively), the maximum values of the cross-correlation function and the corresponding phase shifts were determined.

The cross-correlation sequence for each joint pair (and club-joint pair) is generated from the velocity data between onset and offset (i.e. comparing the pattern of two sets of velocity data over the total number of frames within the golf swing duration), allowing the highest cross-correlation and the corresponding phase shift to be derived (i.e. where the maximum cross-correlation between the two joint patterns occurs in relation to zero shift). This was generated by use of MATLAB algorithms from non-filtered data, hence, all 240 data points (frames) per seconds were used for these calculations. In addition, we also examined coupling strength between both shoulders (inter-limb coupling) during the golf-swing movement. These time-series analyses were performed for all golf-swing trials (time between onset to offset) with successful recordings of all joint markers and club base markers (Figure 3(a),(b)). The cross-correlation functions of the shoulder, elbow, and wrist of each side and the club base marker were compared at the phase shift delivering the maximum cross-correlation values.

The maximum cross-correlations and the corresponding phase shifts are depicted in Figure 3(a),(b), respectively. As can be seen, if one signal is shifted from zero, there is a phase shift that may be either positive or negative depending on which signal that is denoted as the reference (Figure 3(b)). In this study, a negative phasing value for joint coupling correlations indicated that the second named segment was lagging the first named segment. For the calculation of maximum cross-correlation values and the corresponding phase shifts (number of frames transformed to ms), data from 382 golf-swing trials was used from the pre-test and 376 from the post-test (in total $n = 758$ trials). The cross-correlation outcomes from each participant (for each pre- and post-test conditions, and club use) were then averaged and analysed following a Fisher Z-transformation (Derrick & Thomas, 2004).

Statistical analysis

All kinematic outcome data were subjected to mixed-design analysis of variance (ANOVAs) with test (pre- and post-test) and club (4-iron, 7-iron, and pitching wedge) being independent variables, and pre- and post-test representing the within-subject repeated measure. All measures (maximum cross-correlation, phase shift, and club base velocity outcomes) were tested for effects of test, club, and interaction. In order to investigate pre- to post-test differences with regard to intra-limb coordination, the outcome from the cross-correlation function between pairs of joints and joints and club base, the corresponding phase shifts were used as dependent variables. Before statistical analyses, the maxima of the

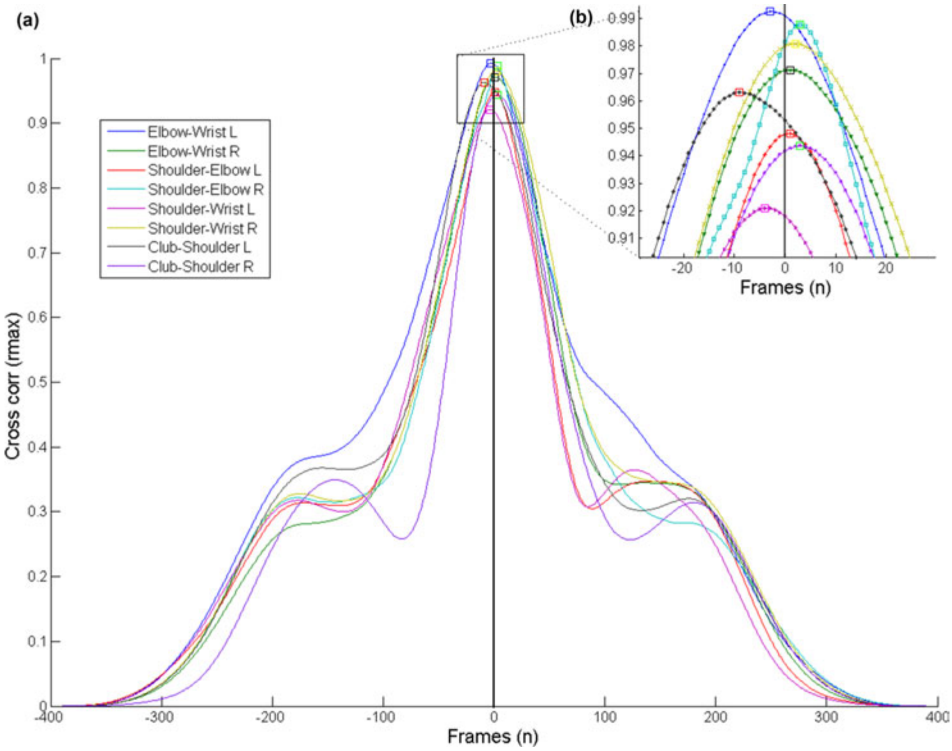

Figure 3. Example of the cross-correlation function extracted from the velocity profiles showing (a) the cross-correlation function between the elbow–wrist, shoulder–elbow, and shoulder–wrist joint couplings for respective arm, and between club and shoulders, calculated for the whole time window of the golf swing (onset to offset), and (b) a close-up of the peak cross-correlation (maximum cross-correlation = horizontal broken line) with the phase shift indicated by the vertical broken line (1 frames = 4.16 ms). L, left; R, right.

cross-correlation function were transformed to Fisher *Z*-scores. Wilk's lambda (λ) was reported for all main and interaction effects and Scheffe's *post hoc* test was used for all significant interactions. Where the sphericity assumption was violated, Greenhouse–Geisser correction was applied. The pre-set level for statistical significance was 0.05 for all analyses, and effect sizes were reported as partial eta-squared (η_p^2).

Results

Intra-limb and inter-limb coordination

For the maximum cross-correlation outcomes, the mixed-design ANOVA revealed a significant main effect of test ($F_{8,29} = 7.07, p < 0.001, \eta_p^2 = 0.32$), but no main effect of club ($p = 0.97$) nor any test × club interaction ($p = 0.92$). Although the *post hoc* analysis did not reveal significant between-test differences for *all* the separate joints couplings investigated, they all showed, including the club base–shoulders and the club base–wrist coupling, higher maximum correlation outcomes at post-test in comparison to pre-test (Table I).

For the phase shifts, a significant effect of test was evident ($F_{8,29} = 7.19$, $p < 0.05$, $\eta_p^2 = 0.66$). No main effect of club use ($p = 0.40$) nor significant interaction between test and club use was found ($p = 0.97$). When analysing the phase shifts for the individual joint couples, the left wrist was found to increasingly lag the left elbow, and the right wrist to

Table I. Maximum cross-correlations during the full golf swing (Mean ± SE).

		Club				
Side/joints	Test	4-iron	7-iron	PW	All	Effect size (η_p^2)
L/elbow–wrist	Pre	0.922 ± 0.011*	0.906 ± 0.012*	0.916 ± 0.011	0.914*	0.69
	Post	0.966 ± 0.012	0.969 ± 0.012	0.961 ± 0.011	0.965	
R/elbow–wrist	Pre	0.913 ± 0.012*	0.924 ± 0.011	0.905 ± 0.013	0.914*	0.46
	Post	0.950 ± 0.008	0.939 ± 0.010	0.942 ± 0.009	0.941	
L/shoulder–elbow	Pre	0.913 ± 0.010	0.912 ± 0.010*	0.918 ± 0.011	0.914*	0.42
	Post	0.943 ± 0.011	0.945 ± 0.011	0.935 ± 0.010	0.941	
R/shoulder–elbow	Pre	0.953 ± 0.004	0.960 ± 0.002	0.955 ± 0.003	0.956*	0.35
	Post	0.968 ± 0.001	0.968 ± 0.001	0.968 ± 0.001	0.968	
L/shoulder–wrist	Pre	0.901 ± 0.009	0.912 ± 0.010	0.907 ± 0.010	0.906	0.14
	Post	0.921 ± 0.011	0.919 ± 0.010	0.911 ± 0.010	0.917	
R/shoulder–wrist	Pre	0.907 ± 0.013*	0.920 ± 0.012	0.895 ± 0.014*	0.907*	0.41
	Post	0.943 ± 0.009	0.932 ± 0.011	0.935 ± 0.010	0.934	
L/club–shoulder	Pre	0.925 ± 0.008	0.926 ± 0.008	0.932 ± 0.008	0.928	0.12
	Post	0.932 ± 0.008	0.935 ± 0.009	0.936 ± 0.009	0.934	
R/club–shoulder	Pre	0.952 ± 0.004	0.944 ± 0.005	0.936 ± 0.005	0.944*	0.35
	Post	0.961 ± 0.002	0.955 ± 0.003	0.948 ± 0.003	0.956	
L/club–wrist	Pre	0.970 ± 0.013	0.965 ± 0.010	0.962 ± 0.004	0.965	0.04
	Post	0.973 ± 0.011	0.967 ± 0.006	0.968 ± 0.003	0.970	
R/club–wrist	Pre	0.958 ± 0.011	0.935 ± 0.009	0.932 ± 0.011	0.942*	0.38
	Post	0.960 ± 0.007	0.952 ± 0.004	0.953 ± 0.008	0.955	
Left shoulder–right shoulder	Pre	0.925 ± 0.009	0.921 ± 0.006	0.927 ± 0.012	0.925*	0.20
	Post	0.930 ± 0.003	0.931 ± 0.002	0.932 ± 0.003	0.931	

Notes: L, left; R, right; PW, pitching wedge; SE, standard error. *Significantly different from the matching post-test value ($p < 0.05$).

decreasingly lead the right elbow at post-test in comparison to pre-test. Here, the tendency of the phase shifts of both joint couplings is to approach a zero-lag. For the left shoulder–left wrist phase shift, the left wrist was lagging the left shoulder to a greater extent at the post-test in comparison to the pre-test. In addition, a significant club base–left wrist shift difference was found by means of the left wrist leading the club base to a lesser degree at post-test (see Table II). An interesting observation is that the couplings on the left side of the body (elbow–wrist, shoulder–elbow, and shoulder–wrist) all indicate that proximal segments are leading the distal segments, whereas for the joint couplings on the right body side (elbow–wrist, shoulder–elbow, and shoulder–wrist) the distal segments are leading the proximal segments. Also, for the phase shifts of the respective joint pairs, keeping with the outcome for the maximum cross-correlation, the joint pairs of the right arm during the golf swing showed somewhat less phase shifts in comparison to the joint pairs on the left side (Table II).

Club base velocity

Separate mixed-design ANOVAs were conducted on the three velocity outcomes from the club-base marker (peak velocity backswing, velocity at the end of the backswing, and velocity at ball impact). For *peak velocity backswing*, no main effect of test ($p = 0.09$), club use ($p = 0.97$), or interaction between test and club use ($p = 0.98$) was found. In agreement with these findings, no main effect of test ($p = 0.35$), club use ($p = 0.90$), or interaction between test and club use ($p = 0.71$) was found for *velocity at the end of the backswing*. In addition, there were no main effect of test ($p = 0.62$), club ($p = 0.99$), or interaction between test and club use found in regard to *velocity at ball impact* ($p = 0.97$) (Figure 4).

Discussion and implications

Recent research has shown that timing-based interventions (i.e. practice with focus on synchronizing hand and foot movements with rhythmic auditory stimuli) may produce both specific (e.g. Sommer & Rönnqvist, 2009) and generalized changes (e.g. Cosper et al., 2009; Johansson et al., 2012) in a variety of human behaviours. However, less is known about if and how SMT may facilitate complex multi-joint coordination such as during the course of a golf swing. Thus, the present study is the first to examine the effect of SMT on kinematic properties in the upper limbs in golf-swing performance. In summary, this study provides new evidence that improved motor timing, as an effect of 4 weeks of SMT, induces changes in the coordinative structure (dynamics) and the temporal synchronicity between joint couplings of the arms as well as between individual joints and the golf club motions during the golf swing. Furthermore, it demonstrates a decreased variance in the joint couplings after SMT training.

Temporal synchronicity between joints

Current advances in the field of nonlinear dynamics have shown that collective variables, such as relative phase shifting, are able to capture the underlying spatiotemporal dynamics of intra-joint coordination (e.g. Burgess-Limerick, Abernethy, & Neal, 1993), and the relationships between different joints to describe intrinsic dynamics (e.g. Kelso, Buchanan, & Wallace, 1991). In line with these concepts as well as with our predictions, the findings from the present pre- to post-test comparison of spatiotemporal properties during golf-swing performance suggest that improved motor timing, as an effect of SMT, reinforces the coordinative structure and the temporal synchronicity between intra-limb couplings and the

Table II. Summary of phase shifts at the maximum cross-correlation for the full golf swing (in ms; Mean ± SE).

		Club				
Side/joints	Test	4-iron	7-iron	PW	All	Effect size (η_p^2)
L/elbow–wrist	Pre	-2.9 ± 2.4*	-5.8 ± 2.6	-4.0 ± 2.5*	-4.2 ± 2.5*	0.31
	Post	-9.8 ± 2.5	-2.5 ± 2.4	-13.3 ± 2.5	-11.1 ± 2.6	
R/elbow–wrist	Pre	3.1 ± 1.6	7.9 ± 1.7	8.3 ± 1.6	6.5 ± 1.7*	0.36
	Post	1.1 ± 1.6	2.4 ± 1.6	1.9 ± 1.6	2.1 ± 1.6	
L/shoulder–elbow	Pre	-4.3 ± 2.0	-2.3 ± 2.1	-10.4 ± 1.1	-5.7 ± 2.1	0.17
	Post	-1.5 ± 2.0	-3.3 ± 2.0	-4.0 ± 2.0	-2.9 ± 1.9	
R/shoulder–elbow	Pre	-7.7 ± 2.0	-3.0 ± 2.2	2.5 ± 2.1	-2.7 ± 2.1	0.24
	Post	4.3 ± 2.1	4.8 ± 2.1	5.7 ± 2.1	4.9 ± 2.1	
L/shoulder–wrist	Pre	-16.1 ± 2.5	-17.4 ± 2.6	-25.1 ± 2.6	-19.5 ± 2.3*	0.28
	Post	-2.6 ± 2.6	-22.2 ± 2.6	-27.7 ± 2.6	-23.4 ± 2.2	
R/shoulder–wrist	Pre	-0.1 ± 2.1	2.6 ± 2.2	4.5 ± 2.1	2.3 ± 2.1	0.21
	Post	2.2 ± 2.1	4.8 ± 2.1	5.4 ± 2.1	4.1 ± 2.1	
L/club–shoulder	Pre	34.9 ± 1.9	33.8 ± 2.0*	28.9 ± 1.9	32.5 ± 1.9	0.16
	Post	31.3 ± 2.0	28.6 ± 1.9	25.3 ± 2.0	28.4 ± 1.7	
R/club–shoulder	Pre	11.8 ± 2.8	9.8 ± 3.0	1.8 ± 4.0	7.7 ± 2.4	0.02
	Post	10.8 ± 2.9	7.1 ± 2.9	2.1 ± 2.9	6.6 ± 2.4	
L/club–wrist	Pre	20.5 ± 2.8	22.1 ± 2.4	16.1 ± 3.5	19.5 ± 0.8*	0.31
	Post	13.5 ± 7.8	14.1 ± 7.3	6.3 ± 8.0	10.4 ± 1.2	
R/club–wrist	Pre	6.1 ± 2.3	6.8 ± 1.9	3.7 ± 1.9	4.9 ± 0.7	0.07
	Post	7.4 ± 2.3	6.5 ± 2.4	3.0 ± 2.0	5.6 ± 0.5	
Left shoulder–right shoulder	Pre	-32.0 ± 6.4	-34.7 ± 7.6	-46.9 ± 7.1	-37.6 ± 1.6	0.02
	Post	-31.4 ± 6.4	-37.0 ± 7.1	-39.6 ± 7.0	-35.8 ± 1.5	

Notes: L, left; R, right; PW, pitching wedge; SE, standard error; ms, milliseconds. *Significantly different from the matching post-test value ($p < 0.05$).

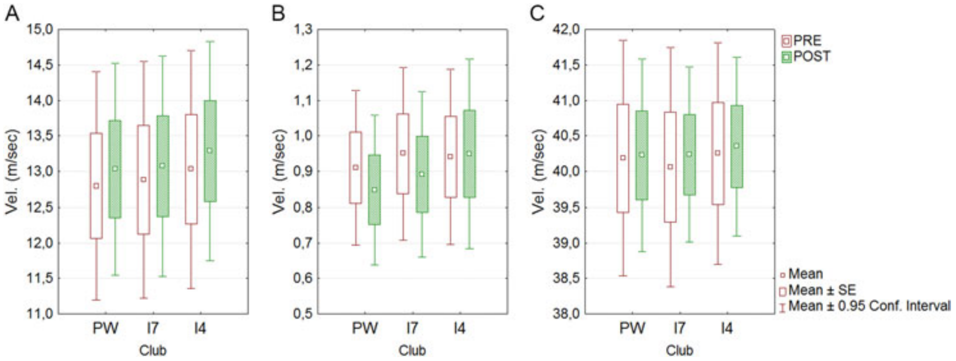

Figure 4. Velocity outcomes generated from the club base marker as a function of club and test: (A) peak velocity backswing, (B) velocity at the end of the backswing, and (C) velocity at ball impact.

golf club motions. We found significantly higher cross-correlation values between joint couplings and concomitant changes of the associated phase-shift differences, and in general, reduced phase-shift variability from zero post SMT. Together, the data indicate that improved motor timing, as assessed by the IM timing and rhythmicity test, do have effect on the temporal properties of the upper-body motions of golf-swing performance, producing a more coordinated and dynamic swing performance. Thus, the interpretation is that improvements in motor timing as an effect of SMT can seemingly be transferred to an unrelated motor task; in this case, the intrinsic movement sequencing during the golf-swing performance. This is in agreement with the assumption of the described phenomenon in bimanual polyrhythmic tapping: that there are structural aspects of timing that can be generalized across different rhythmical tasks (Treffner & Turvey, 1993). Furthermore, and in support of this assumption, it has been shown in optimization models that a rhythmic cue may result in complete specification of the dynamics of the movement over the entire movement cycle, reducing variability, enhancing temporal precision, and facilitating the selection of optimal movement trajectories, velocity, and the acceleration parameters (Thaut & Kenyon, 2003).

Zelaznik and colleagues (Robertson et al., 1999; Zelaznik, Spencer, & Doffin, 2000; Zelaznik, Spencer, & Ivry, 2002, 2005) proposed that timing and rhythmic movements are achieved by using different control strategies, depending on the task specificity. Accordingly, during successive timing tasks (such as finger tapping), every interval is explicitly timed, whereas during continuous rhythmic movement (such as continuous circle drawing), timing is achieved implicitly. This suggests that through auditive feedback of the performance during timing tasks as in SMT, each synchronized interval have to be explicitly timed, by adjusting and fine tuning the central representation of the timed beat interval. However, when complexity of the movement sequence increases such as during the golf-swing performance, the rhythmic sub-movements seem to be consisting of both implicit and explicit timing strategies. Our interpretation of the SMT effects found on the kinematic properties (by means of seemingly more tightly coupled joint dynamics during the golf swing) is that it is reinforced implicitly and then consolidated and represented in the motor memory. Thus, this would suggest that the timing training induced neural adaptations (plasticity). Hence, this is in line with McGrew's assumption (2013): that SMT may result in increased brain communication efficiency between brain regions, especially those related to more domain-general motor functions (e.g. cerebellum and the supplementary motor areas).

Decreased variability in joint couplings

In order to improve the golf score, the golfer must optimally organize and repeatedly produce successful complex swing movements (McHardy & Pollard, 2005). However, the dynamic system theory suggests that high-level performance in sports like golf would benefit from some degrees of functional variability in swing positions (Knight, 2004). Newell and James (2008) concluded in their synthesis of recent findings that the amount of variability in the movement outcome in most motor tasks is inversely related to the amount of variability in the underlying movement dynamics that produce the outcome. In agreement with Glazier (2011), we believe that the specific type of variability being examined and the level of dynamics referred to, are of high importance and should be considered. However, so far, most studies of golf performances have investigated movement variability at club impact and/or of specific outcome parameters at different phases of the golf swing, and not the underlying movement dynamics and coordination patterns throughout the golf-swing performance as was the case in the present study.

The major goal, and challenge, of any golfer is to consistently and predictably hit the ball in the desired direction for the proper distance, independent of strategy. In view of this, Knight (2004) suggests that if any invariance of golf-swing kinematics is sought, it should be at ball impact, where the outcome is determined. We generally agree with this reasoning. However, the interpretation of the time-series analysis of the golf-swing performance in the present study indicates less variability in the underlying movement dynamics, as an effect of SMT. This fits with the notion that variability should only be minimized in the (swing) components that have the greatest effect on the variability of the outcome (e.g. Knight, 2004; Todorov & Jordan, 2002). Accordingly, the improved motor timing found as an effect of the SMT implied a decreased variability in the temporal structure of the swing motion. These findings are in accordance with the decrease of variability and the smoother movement trajectory found as an effect of rhythmic cuing in hemiparetic reach (Malcolm et al., 2009; Thaut, Kenyon, Hurt, McIntosh, & Hoemberg, 2002), and of SMT in children with spastic hemiplegia (Johansson et al., 2012). Moreover, the decreased variability in the coordinative structures of the golf-swing performance was accompanied by decreased golf-shot outcome variability and increased golf-shot accuracy (cf. Sommer & Rönnqvist, 2009).

The present results may provide interesting implications also for other motor skills/sport activities than golf. If SMT improves temporal skills and movement performance by fine-tuning the timing components (and coordination dynamics) of multi-joint movements, then this type of training may also be used to improve performance in other activities that require precise (and/or increased) timing abilities. However, it should be taken into consideration that our applied design lack a control group, and the sample in focus is not as extensive as to claim that the results previously mentioned could easily be extrapolated. Therefore, continued systematic studies are needed to further explore the usefulness of SMT across a wide range of sport activities and in different age spans, as well as in various clinical conditions, all with the goal of improving movement performance by means of timing, motor planning, and sequencing. In addition, questions of training dose, individual consolidation and long-term effects remain unanswered. If the findings of increasing joint-couplings and decreasing variance as an effect of SMT may induce increasing functional variability of the golf swing under different conditions and environmental constraints, in line with a dynamic system perspective, are yet to be further investigated.

In regard to findings indicating a proximal to distal sequencing of peak segmental angular velocities in the golf downswing (e.g. Cheetham et al., 2008; Neal et al., 2008), the present study confirmed such results. However, this was true only for the leading arm (left arm in this case). For the right arm, the opposite (distal to proximal) sequencing of peak segmental angular velocities was more apparent. To our knowledge, no investigation of the spatiotemporal characteristics of the work of the non-leading arm during the golf swing has been conducted. Thus, imminent studies ought to investigate the sequencing of peak segmental angular velocities also in the non-leading arm across skill levels, and between genders.

Further studies are also recommended to investigate sex differences as well as kinematic analysis of sternum and hips markers in order to provide important information of movements of other body parts (e.g. Hume, Koegh, & Reid, 2006; Zheng, Barrentine, Fleisig, & Andrews, 2008b). This would lead to an even more comprehensive understanding of the effects of SMT on golf-swing performance. Finally, we believe that it is highly important to investigate the effect of SMT on brain organization, functions, and neuroplasticity in relation to skilled motor performance, matters that we are currently focusing on in ongoing research projects.

Conclusion

Our findings indicate that SMT influences the underlying coordinative structures and the temporal synchronicity of the upper-limb movements involved during the golf-swing performance. A consistent finding was the significant higher cross-correlation values of the intra- and inter-joints couplings at the post-test in comparison to the pre-test, and a concomitant significant change in the corresponding shifts from zero-lag. These results indicate that improved motor timing as an effect of SMT does influence the dynamics and underlying timing properties of the golf-swing motion, mediated by the coordinative structure and the temporal synchrony between joint couplings involved during the golf-swing performance. These findings adds both to our recent results of improvements of golf-shot outcome accuracy as an effect of SMT (Sommer & Rönnqvist, 2009) as well as to similar results reported by Libkuman et al. (2002). Furthermore, the use of time-series analysis on the velocity profiles to investigate the effects of SMT on the full golf swing highlights the effects on timing and joint couplings. Thus, this analysis provides information that may not have been revealed by examining simple velocity peaks and their timing at different swing phases in isolation. Along this line, application of time-series analysis may be used with the aim to determine golfer's stability and variability of the repeated swing performance, to distinguish skill levels, and to evaluate the effect of different training methods.

Acknowledgements

This study was supported by grants from the Swedish National Centre for Research in Sports, and from the Swedish Research Council, sponsoring of the motion capture system, to the third author. The authors thank Anna-Maria Johansson for assisting with the IM intervention program and Andrew Wallace for MATLAB programming. Sincere appreciation is also expressed to the participating golfers for their commitment to the study.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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