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Investigating the Social Behavioral Dynamics and Differentiation of Skill in a Martial Arts Technique

Robert R. Caron,
Assumption College

Charles A. Coey,
College of the Holy Cross

Ashley N. Dhaim, and
University of Connecticut

R. C. Schmidt
College of the Holy Cross

Abstract

Coordinating interpersonal motor activity is crucial in martial arts, where managing spatiotemporal parameters is emphasized to produce effective techniques. Modeling arm movements in an Aikido technique as coupled oscillators, we investigated whether more-skilled participants would adapt to the perturbation of weighted arms in different and predictable ways compared to less-skilled participants. Thirty-four participants ranging from complete novice to veterans of more than twenty years were asked to perform an Aikido exercise with a repeated attack and response, resulting in a period of steady-state coordination, followed by a take down. We used mean relative phase and its variability to measure the steady-state dynamics of both the inter- and intrapersonal coordination. Our findings suggest that interpersonal coordination of less-skilled participants is disrupted in highly predictable ways based on oscillatory dynamics; however, more-skilled participants overcome these natural dynamics to maintain critical performance variables. Interestingly, the more-skilled participants exhibited more variability in their intrapersonal dynamics while meeting these interpersonal demands. This work lends insight to the development of skill in competitive social motor activities.

Considerable attention is being given to the behavioral dynamics perspective to further our understanding of how skill emerges in athletic endeavors (Seifert, Button, & Davids, 2013; Davids, Button, Araújo, Renshaw, & Hristovski, 2006). Behavioral dynamics combines the perception-action coupling of ecological psychology (Warren, 2006), where an

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Correspondence concerning this article should be address to Robert R. Caron, Department of Human Services and Rehabilitation Studies, Assumption College, Worcester, MA 01609. rrcaron@gmail.com.

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interdependent relationship between an actor and their environment is emphasized (Gibson, 1966, 1979), with the computational generality of dynamical systems theory, where patterns in the physical world are modeled in non-linear, self-organizing, and complex systems terms (Kelso, 1995). This approach to understanding how humans coordinate the movement of their own bodies in space, and their actions with the actions of others, contrasts sharply with approaches that rely upon representational mental models (R. A. Schmidt & Lee, 2005), and motor programs (Summers & Anson, 2009), which instead explain behavior by positing remarkable predictive abilities of the central nervous system to send motor commands to a compliant body.

One of the fundamental criticisms of these representational approaches is what Nikolai Bernstein (1967) described as a "degrees of freedom problem", whereby a highly redundant movement system composed of numerous different parts needs to reduce its many degrees of freedom in order to achieve coordinated movement (Turvey, 1990). As a solution to this problem, the behavioral dynamics approach proposes that functional movement emerges out of an interaction of enabling constraints, which originate from the organism, environment, and task, and limit those degrees of freedom (Davids, Button, & Bennett, 2008; Glazier & Davids, 2009; Holt, 1998; Newell, 1989; Saltzman & Kelso, 1987). Thus, performance of complex tasks requires a temporary assembly of body segments that are constrained in order to limit joint space degrees of freedom in service of some goal or outcome (Kugler, Kelso, & Turvey, 1980, 1982). This goal-directed assembly is often referred to as a *coordinative structure* or *functional synergy* (Turvey, 1990), and is organized in direct relationship with an information-rich environment (Fajen, Riley & Turvey, 2008).

One example of such functional synergies is the rhythmic interlimb coordination that occurs during locomotion. The behavioral patterns of such synergies have been modeled as a system of coupled nonlinear oscillators with signature symmetry properties, and inter-pattern transitions as symmetry-breaking bifurcations (Haken, Kelso, & Bunz, 1985; Haken, Kelso, Fuchs, & Pandya, 1990) thereby capturing both locomotory steady states and gait transitions (Wagenaar & Van Emmerik, 1994; Kelso & Jeka, 1992). In other words, during locomotion different body segments, which can potentially move independently of one another, display the same patterns of coordinated movement described by a system of coupled oscillators. In general, these coordination dynamics do not necessarily rely on any form of computation or representation, but instead can emerge naturally from the coupling and constraints imposed within the system of oscillators (Schmidt & Richardson, 2008).

Interestingly, these generalized rhythmic coordination dynamics have also been observed in the interpersonal coordination of perceptually coupled co-actors, in tasks such as interpersonal pendulum swinging (Schmidt & Turvey, 1994), chair rocking (Richardson et al., 2007) or playing pat-a-cake (Schmidt et al., 2011). As in the intrapersonal case, these behaviors can be mathematically modeled in a manner that captures the cooperative and competitive forces acting upon the joint system of coupled oscillators (Amazeen, Amazeen, & Turvey, 1998). Moreover, these same dynamics are evident whether the coordination is intentional, with people being instructed to deliberately coordinate their movements (Richardson et al., 2007; Schmidt et al., 1990, 1998), or spontaneous, as often occurs in natural social interactions (Issartel, Marin, & Cadopi, 2007; Miles et al., 2011; Oullier et al., 2008; Richardson et al., 2007; Schmidt & O'Brien, 1997; van Ulzen et al., 2008).

These findings raise an important question as to the existence of *interpersonal synergies* (Schmidt & Fitzpatrick, 2016), functional coordinative structures comprised of components from different co-actors, which are further comprised of embedded intrapersonal synergies (e.g., Coey et al., 2011). This interpersonal synergy concept is useful in applying the behavioral dynamics approach to sport and athletic interactions. Theoretically, establishing the requisite coupling and constraints at the level of perception-action creates a synergy between team members and/or between competitors, and means that actors within these interpersonal synergies will reciprocally compensate for one another's actions, behaving as an integrated whole. Consequently, the establishment of these interpersonal synergies would greatly reduce the degrees of freedom of the interpersonal system and would suggest that they should display relatively low-dimensional dynamics that could potentially be captured by existing dynamical models. A central question in furthering the behavioral dynamics account of sport is how training and skill allows actors to affect the assembly of these interpersonal synergies as well as override them when it is advantageous to do so. In the present study, we explore the role that skill has in the behavioral dynamics of interpersonal synergies within the context of a dyadic competitive sports interaction.

Dynamics of Competitive Sport Interactions

A growing body of literature has focused on how ecological and dynamical systems theories can be used to understand the interpersonal interactions observed in competitive sports (Davids et al., 2006; McGarry et al., 2002). This research has noted that many sports involve an inherent rhythmic component, such as the alternating volleys of tennis (Palut & Zanone, 2005) and squash (McGarry & Walter, 2007), or the ebb and flow movement from one end of the field to another in soccer (Frencken & Lemmink, 2008) or basketball (Bourbousson et al., 2010a, 2010b). Moreover, the rhythmic play of individuals and teams tend to be synchronized and can be modeled as a coupled oscillatory regime (McGarry et al., 2002) similar to that used to model interpersonal interlimb coordination (Schmidt & Richardson, 2008).

The dynamics of continuous rhythmic coordination are well-captured by the HKB model (Haken et al., 1985; Schöner et al., 1986):

$$\dot{\phi} = \Delta\omega - a \sin \phi - 2b \sin 2\phi + \sqrt{Q}\zeta$$

The model describes the change in the *relative phase* (ϕ) between two oscillatory components, which can simply be understood as the spatiotemporal difference between where two oscillators are in their respective cycles. The model predicts two stable modes of relative phase; *in-phase* coordination ($\phi = 0°$), where the oscillators consistently mirror one another in their individual cycles throughout the movement and *anti-phase* coordination ($\phi = 180°$), where the oscillators are consistently opposing each other in their movement cycles. The model specifies that the exact form of coordination depends on certain parameters. First, coordination depends on the *coupling strength* (indexed by b/a), which concerns how much force the oscillators exert on one another. When coupling strength is high, the oscillators will quickly fall into a pattern of coordination and tend to hold it despite perturbations. When the coupling strength is low, the coordination is weaker and, if it is low enough, only the in-phase mode will remain stable (e.g., Schmidt et al., 1990). Second, the coordination depends on the *detuning* ($\Delta\omega$), which concerns the difference in the natural frequencies of the two oscillators. If there is considerable detuning, the inherently faster oscillator will tend to "lead" the coordination and the slower will tend to lag behind. Lastly, the coordination depends on the strength of *noise* ($Q\zeta$), which concerns how much random variability is present in the coordination. These three parameters interact to influence the coordination. For instance, when the coupling strength is very high, it will tend to counteract the influence of detuning and noise, so that the oscillators will demonstrate more stable coordination with minimal phase lead/lag. Interestingly, although the standard HKB model assumes that the noise term $Q\zeta$ remains constant with changes in detuning ($\Delta\omega$) and coupling strength (b/a), more recent work has demonstrated that scaling the frequency of component oscillators away from their eigenfrequencies may increase the noise $Q\zeta$ itself contrary to the standard assumption (Richardson, Schmidt, & Kay, 2007).

The HKB model has been used to understand certain sport interactions quite well, particularly when the task movements involve a clear rhythmic performance. For example, Palut and Zanone (2005) used it to understand the interpersonal coordination in tennis volleys demonstrating that the canonical phase modes of in-phase and anti-phase emerge from the participants' movements across the court. Schmidt and colleagues (2011) used it as well to investigate the effect of detuning on a cooperative interpersonal sword-swinging task. In this study, participants stood facing a partner, and coordinated the rhythmic swinging of their swords. The weight of the swords was manipulated between the participants, manipulating detuning, with the lighter swords having a faster intrinsic frequency than the heavier swords. Consistent with the predictions of the HKB model, the coordination between the participants showed the expected phase lead/lag relationships: Although the swinging was synchronized, participants with heavier swords tended to lag behind their partners with lighter swords. The authors argued that these findings supported the behavioral dynamics approach to understanding joint action. The coordination exhibited by the participants obeyed the dynamics known to govern systems of coupled oscillators in general.

Importantly, however, the results also demonstrated that experienced participants, who were martial arts students familiar with such tasks, showed substantially less phase lead/lag than their unskilled counterparts. That is, the more-skilled participants remained closer to perfect in-phase coordination ($\phi = 0°$) than did the less-skilled participants, despite being subject to the same level of physical detuning. This raises important questions as to how the behavioral dynamics perspective might approach the role of skill and training in human interactions. In particular, a relevant question is whether or not more-skilled actors can exploit the natural dynamics of the coupled oscillatory regime to gain some advantage in the interaction.

Differentiation of Skill

Competitive sports provide a rich test bed for understanding skill in complex interactions, as success on the court or field is determined, in part, by the ability of actors to coordinate their actions, and perhaps flexibly interrupt or break certain forms of coordination to take some advantage in the competitive interaction (Davids et. al., 2006). Understanding the development of athletic skill in terms of coordination is an area of research that has recently expanded using both single athletes (Williams et al., 2016) and teams (Silva et al., 2014). Athletic endeavors require both intra- and interpersonal coordination to achieve the goal. For example, basketball players must coordinate their body to achieve the tasks of running, dribbling, and shooting the ball; however, they must also do so in relation to a defender that is often acting as an obstacle.

The establishment and breaking of such interpersonal synergies has been frequently observed in sports (Araújo & Davids, 2004; McGarry et al., 2002). Araújo and colleagues (2002) noted how defending soccer players established a synergy with an attacker, and attempted to remain between the attacker and the goal. In contrast, the attacker must destabilize this synergy in order to dribble past the attacker and get a clear shot on goal. The interpersonal distance between attacker and defender, as well as the distance to the goal, form a dynamic system in which the attacker must destabilize the established stable state in order to take an advantage (Araújo et al., 2002; Araújo, Davids, & Hristovski, 2006). McGarry and colleagues (2002) noted a similar strategic destabilization when an attacker in a squash match would perform a shot that violated a stable exchange in order to score.

Understanding the development of skill in these kinds of sports interactions requires the assessment of variability in coordination in addition to assessing stable coordination patterns. Several studies have suggested that variability is a basic measure of skilled movement (Williams et al., 2016; Komar, Seifert, & Thouvarecq, 2015; Müller & Sternad, 2004; Latash, Scholz, & Schöner, 2002). Generally, it appears that some optimal range of variability exists for any given task, whereby too much variability suggests an inability to develop a stable coordinative structure, which leads to poor performance (Chow et al., 2008). In contrast, too little variability suggests a lack of flexibility to deal with changing dynamics in the environment or task space (Wilson et al., 2008; Davids et al., 2003), and can similarly lead to poor performance. Thus, it is generally expected that skilled movement and successful task performance entails a balance of stability and flexibility, and that excessive variability might reflect a breakdown of a synergy and a destabilization of the performance variable being controlled (Black, Riley, & McCord, 2007; Latash, et al., 2002).

Although research from the behavioral dynamics perspective on the role of skill in sport interactions is relatively limited, there are two central points to be considered. First, the task performance involved in these interactions requires both the establishment and the breaking of certain forms of coordination. A skilled actor must be able to break coordination at a critical moment in order to achieve an advantage over an opponent. Second, skilled performance involves some balance of stability and variability in the coordination, with too much or too little variability potentially resulting in overly random or overly rigid performance. An important question is whether skill development involves the ability to manipulate the stable dynamics involved in the task and whether this skill is evident in the form of the coordination or in its associated variability. Do more-skilled athletes seek an advantage within the stable state, prior to destabilizing the established coordination? Will this skill be evident in the coordination, perhaps as slight phase leads or lags, or greater or lesser variability? These subtleties of skill demand further study.

Current Study

In the present study, we examine the effect of skill in terms of coordination patterns in a competitive sports task. Most past research from the behavioral dynamics perspective has focused on the intrapersonal coordination of a single person (e.g., Williams et al., 2016) or the group dynamics of a whole team (e.g., Frencken & Lemmink, 2008; Bourbousson et al., 2010a, 2010b). Also, many of the studies that investigate interpersonal coordination have used highly stereotyped movement tasks (e.g., pendulum swinging; Amazeen, Turvey & Schmidt., 1995), which are generally unlike the behaviors characterizing natural social interactions (Sebanz & Knoblich, 2009). Even the aforementioned sword-swinging study (Schmidt et al., 2011) involved the two participants performing identical, sinusoidal movements. Thus, in the current study, we aimed to advance the current research on the behavioral dynamics approach to skilled joint actions by addressing these limitations.

We considered a martial arts task to provide an ideal platform to study such interactions, as the movements involved are performed in relatively tight timescales with complementary but not identical movements, requiring the careful control of spatiotemporal parameters at the cost of potentially being hit by an attacker. We had pairs of participants, an attacker and defender, perform a commonly applied exercise in a martial art called Aikido. The exercise involved the attacker performing an overhead strike to the forehead of their partner and the defender stepping forward and lateral to the defender’s line of attack to intercept the incoming strike (see Figure 1). Unlike the previous study of sword-swinging (Schmidt et al., 2011), the actions for the two participants in the current task are not identical but complementary, and are not cooperative insofar as the ultimate goal for the attacker is not to synchronize with the defender, rather to strike them on the forehead. As a skilled response to such an attack, Aikido as a martial art, posits that the defender ought to synchronize with the attacker’s movements as an optimal strategy to harmonize with, and then lead, the attacker to a non-violent resolution. Thus, the current task more realistically represents a generalizable application of social coordination in competitive sport, where one person (i.e., the attacker) is attempting to perform an action (i.e., the strike to the forehead) and the other person (i.e., the defender) is attempting to intercept or defend against that action (i.e., with a parrying movement). Also, unlike other studies of competitive interactions (e.g., Kijima et al., 2012), the present study measured both interpersonal and intrapersonal coordination dynamics across multiple effectors; allowing us to examine coupled relations at multiple scales in order to capture a more holistic view of the emergent skilled behavior.

With regard to studying how skill might be expressed in coordination patterns, the pairs of participants varied in terms their overall Aikido training and experience with this technique, ranging from pairs that had no training at all (e.g., unskilled undergraduate students) to expert pairs (e.g., black belts in Aikido). We were interested in whether the more-skilled participants would adapt to frequency detuning differently than their less-skilled counterparts. By detuning the natural frequency of their movements, using arm weights to manipulate the difference in the oscillators' inherent frequencies, we assessed how skilled performers dealt with the natural laws governing the dynamics of the coupled oscillators. In line with the findings of Schmidt and colleagues (2011) sword-swinging study, we expected that more-skilled participants might show a stronger dynamical coupling, and hence, less lead/lag in the interpersonal coordination than the less-skilled participants. Additionally, we thought that less-skilled participants would be more impacted by weight and demonstrate greater lag-lead relationships as predicted by the physical dynamics, whereas the more-skilled group may be more adept at overcoming these dynamics in service of successful task performance. We were also interested in how other aspects of coordination might reveal differences in the participants' skill, such as the variability in the interpersonal coordination of their effectors. Generally, we predicted that less-skilled participants would show greater variability in their movement patterns, in part due to the technique being relatively novel to them. However, we also expected that the presence of weight (detuning) would introduce noise $Q\zeta$ into the system for all participants and would likely result in an increase of variability even within the more-skilled group. Although our main objective was to assess the interpersonal coordination dynamics that emerge within a competitive task space, we expected that patterns within the interpersonal synergies observed will be related to the form of the intrapersonal coordination, thus highlighting the nested nature of interpersonal and intrapersonal synergies (Ramenzoni et al, 2011; Schmidt & Richardson, 2008).

Overall, we sought to understand the effects of skilled movement in a dyadic competitive martial arts exercise with specific attention to both the emergent patterns of coordination and the strength, stability and flexibility of their underlying synchronization dynamics. By measuring critical spatiotemporal relationships between the two actors, we hoped to see a competitive advantage emerge in the dynamic that might differentiate more- from less-skilled actors. Finally, we looked for important relationships between the interpersonal and intrapersonal dynamics to more deeply understand the movement strategies employed by actors of different skill levels.

Method

Participants

Thirty-eight adults were recruited to participate in the study (25 males, 13 females, ages 19 to 64 years). All participants reported no current musculoskeletal injuries that would prevent them from participating in moderately strenuous physical activity. The Institutional Review Board of the College of the Holy Cross approved the study and participants provided written informed consent. Participants were grouped into pairs based upon their experience and rank in the martial art, Aikido. Eight participants, recruited from the student body at the College of the Holy Cross, had no experience whatsoever with Aikido and were paired with each other as unskilled participants. Twenty-six participants were recruited from Zenshinkan Dojo, an Aikido school in Worcester, Massachusetts, and were paired together based on their rank in Aikido, with white and yellow belts grouped together as novices, blue and brown belts grouped together as intermediates, and black belts of all ranks (1st – 5th) grouped together as experts.

Materials

To manipulate frequency detuning, 2.5 lbs weights were attached to each of the participants' wrists in accordance with the procedure explained below. The weights used were standard wrist/ankle weights, typically used for exercise, filled with sand and wrapped firmly around the wrist with Velcro straps. Three-dimensional kinematic data were recorded at 120 Hz using a Polhemus wireless G4 movement measuring system (Polhemus, Corporation, Colchester, VT). Sensors on the attacker were attached to his/her sternum, right wrist, and right elbow using straps and gloves with Velcro. Sensors on the defender were similarly attached to his/her sternum, right wrist, and left wrist.

Procedure

Each pair of participants watched a five-minute instructional video on the Aikido task to be completed, which was produced specifically for this study by two of the investigators, who hold a 5th degree black belt and brown belt in Aikido, respectively. All participants were asked to perform a specific Aikido technique called *shomenuchi ikkyo ura*, which is a common Aikido technique selected for the high degree of synchrony necessary to execute the movement well, however, simplistic enough such that a five-minute instructional video would likely result in novices and unskilled participants being able to perform the technique in a recognizable manner. Participants were randomly assigned either the role of the attacker or the defender for the Aikido technique and maintained that role throughout the trial. Eighteen of the participants recruited from Zenshinkan Dojo volunteered to participate in the study twice by switching their role as attacker or defender; thus, no participant duplicated their role in the technique. This resulted in a total of 26 pairs of participants participating in the study: 4 unskilled, 7 novice, 5 intermediate, and 10 expert pairs. The unskilled and novice pairs were then grouped together to form 11 less-skilled pairs, and the intermediates and experts were grouped together to form 15 more-skilled pairs for the analyses.

After being randomly assigned their roles as attacker or defender and watching the instructional video, each participant was asked to perform their role independent of their partner, performing one trial with the weights on each wrist and one trial without weights (four total independent trials). Then the participants were asked to perform the technique as a coordinated pair. The participants performed nine paired trials, which were organized into three blocks of weighted conditions. Each block consisted of three consecutive trials with each condition. Those conditions consisted of: 1) only the attacker's wrists being weighted (AW), 2) only the defender's wrists being weights (DW), and 3) neither the attacker's nor the defender's wrists being weights (NW). The sequence of blocked weighted conditions was presented in a random order across participant pairs. In each trial, the participants engaged one another five times with an attack and response in order to establish a synchronous dynamic (i.e., a steady-state rhythm). The attacker stepped forward and performed an over-head strike using their right arm aimed at the defender's forehead, while the defender stepped forward and to the side of the attacker, meeting their descending arm with his/her right wrist matching the attacker's right wrist and the defender's left hand matching the attacker's right elbow (i.e., the parry; see Figure 1). On the sixth attack, the defender deflected the strike and led the defender's arm toward the ground resulting in the attacker kneeling on the floor with their right arm secured in a horizontal position by the defender (i.e., the take-down).

Data Analysis

Time series data were analyzed using custom MATLAB (MathWorks, Natick, MA) programs. Missing data were interpolated using a cubic spline. In order to capture our anticipated critical interpersonal performance measures, mean values for relative phase and standard deviation of relative phase were calculated for the following effector pairs for each trial: Defender Wrist – Attacker Elbow (WE), Defender Wrist – Attacker Wrist (WW), and Attacker Sternum – Defender Sternum (SS). A continuous relative phase algorithm (Pikovsky, Rosenblum, & Kurths, 2001) was employed to calculate the relative phase time series for each trial. Once mean relative phase and mean standard deviation of relative phase were calculated for each trial, the means across trials of the relative phase (RP) and the standard deviation of relative phase (SDRP) were calculated for each effector pair for each weighted condition (three trials per weighted condition) and used in the statistical analysis.

Intrapersonal coordination measures were assessed in order to understand structural changes in the intrapersonal coordination strategy employed by our participants as they attempted to maintain the assigned interpersonal task. To accomplish this, for both attacker and defender separately, the following intrapersonal effector pairs were evaluated for each trial: Defender Sternum–Right Wrist, Defender Sternum–Left Wrist, Defender Left Wrist-Right Wrist, Attacker Sternum–Wrist, Attacker Sternum–Elbow, and Attacker Elbow-Wrist. Because intrapersonal relative phasing of the effectors did not conform to a normal distribution (unlike the interpersonal relative phase), we used the distribution of relative phase to observe the changing intrapersonal dynamics across weighted conditions. To calculate the distributions of relative phase for each trial, the frequency of occurrence of the relative phase angles in each of eighteen 20° relative phase regions between −180° and 180° was calculated for each trial (Schmidt & O'Brien, 1997; Richardson, March, & Schmidt, 2005).

For both interpersonal and intrapersonal variables, data within the x-dimension (anterior-posterior) and z-dimension (superior-inferior) were considered separately. We did not include y-dimension data in our analysis because the primary plane of action was in the sagittal plane and very little movement occurred in the lateral (y) dimension. For the purposes of this study, only the data from the five synchronous attack-defense sequences (the steady state portion) were included. Data from the sixth attack and response (the take-down) will be analyzed in a future experimental report.

For the interpersonal variables, mixed Analyses of Variances (ANOVAs) were conducted with within-subjects variables of weight (Attacker Weighted [AW], No Weight [NW], Defender Weighted [DW]), and effector pair (Defender Wrist – Attacker Elbow [WE], Defender Wrist – Attacker Wrist [WW], Attacker Sternum – Defender Sternum [SS]) and a between-subjects variables of skill level (more-skilled, less-skilled) and the dependent variables of the mean relative phase (RP) and the standard deviation of relative phase (SDRP). The x and z dimension data were analyzed separately. Significant results were considered at the $p < .05$ level; however, when we observed marginally significant interactions ($p < .20$) we pursued follow-up tests (Fisher pairwise comparisons and simple effects tests) to examine differences between individual means of the different conditions.

For the intrapersonal variables, separate ANOVA's were conducted for the defender and the attacker. In both cases, the ANOVA's examined weight (Attacker Weighted [AW], No Weight [NW], Defender Weighted [DW]), and phase region (18 regions ranging from -180° to 180°) as within-subjects variables and skill level (more-skilled, less-skilled) as a between-subjects variable. These tests also included a within-subjects variable of effector pair, but the exact marker pairs involved in this variable differed between the defender (Defender Sternum– Right Wrist, Defender Sternum–Left Wrist, Defender Left Wrist–Right Wrist) and the attacker (Attacker Sternum–Wrist, Attacker Sternum–Elbow, and Attacker Elbow–Wrist). The dependent variable in these tests was the percentage of observations in the time series occurring within one of the eighteen phase regions, with strong in-phase coordination yielding a concentration of observations at the 0° phase region and strong anti-phase coordination yielding a concentration at the 180° (or -180°) region. As with the analyses of interpersonal coordination, the x- and z-dimensions of movement were analyzed separately. It is not uncommon for some phase regions to not have any observations, so we used a Greenhouse-Geisser correction to address potential violations of the sphericity assumption for repeated-measures ANOVA.

Results

Interpersonal Coordination: Mean Relative Phase

The ANOVA on the x-dimension (anterior-posterior) data yielded no main effect of skill level; however, it did reveal a main effect of effector ($F(2,46) = 6.41$, $p < .01$, $\eta_p^2 = .22$) and a main effect of weight on the mean relative phase (RP) of the effector pairs in the x-dimension ($F(2,46) = 4.97$, $p < .05$, $\eta_p^2 = .18$). Trends toward two-way interaction effects of effector and skill level ($F(2,46) = 2.45$, $p = .10$, $\eta_p^2 = .10$) and weight and skill level ($F(2,46) = 2.51$, $p = .09$, $\eta_p^2 = .10$) were also found. A trend toward a three-way interaction effect of effector, weight and skill was also found ($F(4,92) = 11.09$, $p = .07$, $\eta_p^2 = .09$). Although the interactions with skill had weak effect sizes, our hypotheses with regard to skill encouraged further exploration. Simple effects tests performed on the 2-way interaction of skill and weight revealed that weight impacted RP for only the less-skilled group ($F(2,46) = 4.95$, $p < .05$, $\eta_p^2 = .31$). Simple effects tests on the 3-way interaction found that only the less skilled group showed differences in RP and only within the WW ($F(2,22) = 5.63$, $p < .05$, $\eta_p^2 = .34$) and WE ($F(2,22) = 5.79$, $p = .01$, $\eta_p^2 = .35$) effector pairs. The SS effector pair produced no differences in RP of any kind. As seen in Figure 2, the less-skilled group demonstrated a predictable lag-lead relationship in RP. For the less-skilled group, the defender led when the attacker was weighted, the defender and attacker were nearly synchronous with no weight, and the defender lagged when the attacker was weighted. For the more-skilled group, the defender always led the attacker ($RP < 180°$) with no significant changes between weight conditions. These results indicate that weight does have an impact on RP and lag-lead relationships in interpersonal coordination in a manner predicted by the dynamical model; however, skill appears to be a significant moderating variable with the more-skilled group being able to overcome predictable effects of weight to maintain a small consistent lead (RP just under 180°) in the coordination task.

The ANOVA on the z-dimension (superior-inferior) data yielded no main effect of skill level; however, it did reveal a main effect of effector on the mean relative phase (RP) of the effector pairs in the z-dimension ($F(2,46) = 36.34$, $p < .001$, $\eta_p^2 = .61$). A slight trend toward a three-way interaction effect of effector, weight, and skill ($F(4,96) = 1.58$, $p = .19$, $\eta_p^2 = .06$), our interested in the effects of skill as well as the fact that the task dynamics constrained the SS effector in the z-dimension to a very limited range of motion, prompted us to unpack this interaction and subsequently to evaluate each of the effectors separately to understand how weight and skill might be impacting each of these interpersonal relationships. First, a post hoc simple effects test revealed that only the WE effector pair showed a trend toward differences in RP and only in the less-skilled group ($F(2,22) = 2.75$, $p = .09$, $\eta_p^2 = .20$). Separate ANOVA’s for each effector pair showed no differences in RP for the SS effector pair in the z-dimension, and the WE effector pair showed no differences in RP as well. While the ANOVA for the WW effector pair produced no main effect of skill on RP, a main effect of weight was found ($F(2,46) = 4.84$, $p = .01$, $\eta_p^2 = .17$). To explore the visual differences observed in the RP of the skilled groups in Figure 3, a simple effects test on skill level and weight was performed and suggested that only the less-skilled group demonstrated predictable differences in RP between weighted conditions ($F(2,46) = 2.75$, $p = .09$, $\eta_p^2 = .20$), whereas the more-skilled group showed no significant differences in RP between weight conditions. Post-hoc, pairwise comparisons of each weighted condition for the separate skill groups represented in Figure 3 revealed that only the less-skilled group differed significantly in RP between the NW and DW conditions ($p < .05$) with a trend toward a difference between the AW and NW conditions ($p = .08$). Consistent with dynamic model predictions, the less-skilled defenders appear to be lagging the attackers in the coordination more when they are weighted. No differences were observed in RP for the more-skilled group. Thus, it appears only the RP of the WW effector pair was impacted by weight in the z-dimension but only for the less-skilled group.

Interpersonal Coordination: Standard Deviation of Relative Phase

A significant main effect of effector pair on the mean SDRP in the x-dimension was found ($F(2,46) = 30.57$, $p < .001$, $\eta_p^2 = .57$), with the WW pair having over twice the SDRP of the other two effector pairs ($p < .001$). Pairwise comparisons of each effector pair showed a slight difference between the SS and WE effector pairs ($p = .075$) with the SS pair consistently showing the least amount of variability. A marginal interaction between weight and skill level was observed ($F(2,46) = 2.02$, $p = .15$, $\eta_p^2 = .08$), and results of a simple effects test revealed that only the more-skilled group demonstrated differences in SDRP ($F(2,46) = 5.13$, $p < .05$, $\eta_p^2 = .32$). Pairwise comparisons of the SDRP for the more-skilled group’s weighted conditions suggested that when either the attacker ($p < .001$) or defender ($p = .08$) in the more-skilled group was weighted, that the more-skilled participants became more variable for all effector pairs combined; however, the less-skilled group always demonstrated a higher level of variability than the more-skilled group overall (see Figure 4). No other significant effects were observed for SDRP in the x-dimension. The SDRP of WW and WE effector pairs in the z-dimension were analyzed separately and a significant main effect of skill was found between groups for the WW effector pair ($F(1,23) = 4.74$, $p < .05$, $\eta_p^2 = .17$), as well as for the WE effector pair ($F(1,23) = 7.46$, $p < .05$, $\eta_p^2 = .25$). Neither a main effect of weight nor an interaction of weight and skill were found, suggesting that within groups weight did not impact the SDRP in the z-dimension. However, for both effector pairs, the more-skilled group demonstrated less variability overall.

In summary, the more-skilled group was less variable than the less-skilled group in all conditions across both dimensions. However, whereas the differences in weight did not significantly affect the variability of the less-skilled group, the variability of the more-skilled group was affected by weight in the x-dimension where they showed greater variability when either the attacker or defender was weighted. This change in variability for the more-skilled group follows the dynamic predictions that weight would increase the variability of the coordination pattern when either participants eigenfrequency was detuned. Note though that weight did not affect variability in the z-dimension for either of the skill groups.

Intrapersonal Coordination: Defender Relative Phase

The ANOVA on intrapersonal coordination in the defender's x-dimension (anterior-posterior) movements revealed a main effect of phase region ($F(1.55, 35.71) = 126.81$, $p < .0005$, $\eta_p^2 = .85$), which reflected strong in-phase coordination for all effectors pairs, with the majority of observations falling between −20° and 20° (65.6%), and a small degree of anti-phase coordination, with a few observations falling between 160 and 180° (6.32%). There were also significant interactions of phase region and effector, ($F(3.04, 69.99) = 14.34$, $p < .0005$, $\eta_p^2 = .38$), and of phase region, effector, and skill level, ($F(3.04, 69.99) = 4.19$, $p = .008$, $\eta_p^2 = .15$). As shown in Figure 5, although both skill groups showed strong in-phase coordination, they differed in the variability of relative phase around the in-phase region, specifically for the Left Wrist-Right Wrist and Sternum–Left Wrist effector pairs. The less-skilled group showed sharp, tightly-concentrated peaks in relative phase, with the left wrist tending to lead both the right wrist and sternum in the coordination. In contrast, the more-skilled group showed greater variability in their distributions of relative phase, especially for the Sternum–Left Wrist effector pair.

Another important difference between the skill groups in the defenders' x-dimension movements concerned the degree of anti-phase coordination. Careful examination of the time series suggested that this anti-phase coordination occurred at a particular point in the movement cycle, likely resulting from the flexion at the right elbow during the parry of the attackers' strikes. Overall, the less-skilled group showed slightly greater anti-phase coordination than the more-skilled group, specifically within the Left Wrist–Right Wrist and Sternum–Right Wrist effector pairs. Moreover, the ANOVA revealed marginally significant interactions of phase region, weight, and skill level, ($F(2.99, 68.78) = 2.22$, $p = .094$, $\eta_\mathrm{p}^2 = .09$), and of phase region, weight, effector, and skill level, ($F(6.01, 138.21) = 1.82$, $p = .099$, $\eta_\mathrm{p}^2 = .07$). These effects were driven by the less-skilled defenders showing roughly the same amount of anti-phase coordination across all weighting conditions, whereas the more-skilled defenders showed less anti-phase coordination in the non-weighted condition (see Figure 6).

The ANOVA on the defender's z-dimension (superior-inferior) movements revealed a significant effect of phase region, ($F(2.13, 49.06) = 258.75$, $p < .0005$, $\eta_p^2 = .92$), a significant interaction of phase region and effector, ($F(2.56, 58.95) = 193.4$, $p < .0005$, $\eta_p^2 = .89$), a significant interaction of phase region, weight, and effector, ($F(5.15, 118.37) = 4.67$, $p = .001$, $\eta_p^2 = .17$), as well as a significant interaction of phase region and skill level, ($F(2.13, 49.06) = 4.51$, $p = .014$, $\eta_p^2 = .16$). Generally, these effects can be understood as products of the task constraints. For instance, the defender's two wrists moved up and down together, resulting in in-phase coordination, whereas the sternum tended to move in anti-phase coordination with the wrists, lowering slightly as the defender stepped forward and raised their arms. Also, the weighting condition affected the coordination between the wrists more strongly than between the wrists and sternum, producing tighter in-phase coordination when the defender was weighted than in the other two weighting conditions. More importantly, the effect involving skill level reflected that the more-skilled participants produced stronger in-phase coordination than did the less-skilled group, particularly for the Left Wrist–Right Wrist effector pair.

In summary, these analyses suggest several subtle, but important differences between the less- and more-skilled defenders' intrapersonal coordination. They indicate that the more-skilled defenders tended to maintain stronger in-phase coordination between their wrists in the z-dimension, raising their arms more synchronously to meet the attackers' strikes. They also indicate that the more-skilled defenders tended to flex less at the right elbow, especially when neither the attacker nor defender were weighted, evidenced by less anti-phase coordination within the Left Wrist–Right Wrist and Sternum–Right Wrist effector pairs in the x-dimension. Most importantly, these analyses show that the more-skilled defenders produced more variable in-phase coordination in the x-dimension (see Figure 5).

Intrapersonal Coordination: Attacker Relative Phase

The ANOVA on the attackers' x-dimension (anterior-posterior) movements revealed only a significant effect of phase region ($F(2.49, 57.3) = 207.87$, $p < .0005$, $\eta_p^2 = .90$) and a significant interaction of phase region and effector ($F(2.83, 65.13) = 42.03$, $p < .0005$, $\eta_p^2 = .65$). All effector pairs produced in-phase coordination, but the coordination was much stronger between the wrist and elbow and between the elbow and sternum than the coordination between the wrist and sternum. There were no significant differences between the skill groups.

The ANOVA on the attackers' z-dimension (superior-inferior) movements revealed a significant effect of phase region ($F(1.52, 35) = 127.67$, $p < .0005$, $\eta_p^2 = .85$), a significant interaction of phase region and effector ($F(1.85, 42.51) = 100.37$, $p < .0005$, $\eta_p^2 = .81$), and a significant interaction of phase region and skill level ($F(1.52, 35) = 9.33$, $p = .001$, $\eta_p^2 = .29$). There was strong in-phase coordination between the Attacker Elbow–Wrist, but anti-phase coordination between the Attacker Sternum–Wrist and Sternum–Elbow, indicating that, similar to the defenders, the attackers' sternum tended to drop slightly as they stepped forward and raised their arm to strike. Also similar to the defenders, the effect of skill reflected much stronger in-phase coordination for the more-skilled group, particularly for the Elbow–Wrist effector pair. There was also some indication of in-phase coordination in the Sternum–Elbow and Sternum– Wrist for the more-skilled participants, largely absent in the less-skilled attackers (Figure 7). Follow-up tests confirmed significant interactions between phase region and skill group within the Sternum–Elbow ($F(1.23, 28.29) = 8.28$, $p = .005$, $\eta_p{}^2 = .27$) and the Sternum–Wrist ($F(1.29, 29.64) = 6.74$, $p = .01$, $\eta_p{}^2 = .23$) effector pairs, separately. The more-skilled attackers tended to continue to drop their sternums as their arms descended during the strike, whereas the less-skilled attackers tended to raise their sternums as their arms descended.

In summary, there were important differences between the less- and more-skilled attackers' intrapersonal coordination, specifically within the z-dimension of movement. The more-skilled attackers maintained very strong in-phase coordination between their elbows and wrists, and showed in-phase coordination between their sternum and arm during the strike. This suggests that the more-skilled attackers executed strikes using their whole body. In contrast, the less-skilled attackers showed weaker in-phase coordination between their elbows and wrists, and no in-phase coordination between their sternums and arms, suggesting that they executed their strikes without the benefit of their whole bodies descending with the strike.

Discussion

The aim of this study was to investigate the dynamics of an interpersonal synergy in a more naturalistic task. The martial arts task chosen also allowed us to evaluate the effect of skill on the interpersonal and intrapersonal coordination dynamics that emerge in a competitive sports task. First, we were interested whether frequency detuning manipulated by weighting the limbs would create the lag-lead relationship predicted by the HKB dynamical model in a naturally complex bodily interaction. Second, we sought to better understand how skill might influence these predictable effects of detuning. Although we expected the interpersonal relative phasing to be affected by frequency detuning, we also expected that the more-skilled participants would demonstrate a stronger dynamical coupling and hence would be less affected by the perturbation of added weight to their wrists in order to maintain critical performance measures, such as interpersonal relative phase, more so than their less-skilled counterparts. In terms of relative phase variability, although we expected it to increase with frequency detuning (when either the attacker or defender was weighted), we speculated that different skill groups might show differences in the variability of both their inter- and intrapersonal coordination. Generally, we expected the less-skilled group to demonstrate higher levels of variability than the more-skilled group. However, we also thought it was possible that the more-skilled group would show more flexibility in their coordination strategy when perturbed with the weights, possibly increasing the noise in their intrapersonal coordination, but maintaining critical interpersonal synergies (e.g., mean relative phase). In particular, we expected to see some changes in the intrapersonal coordination of the more-skilled participants when weighted, which would follow literature supporting the use of flexible coordination strategies in the service of maintaining critical interpersonal synergies (Black et al., 2007).

Coordination Patterns as a Skill Differentiator

The present study supports the well verified observation that humans tend to coordinate their rhythmic movements with each other in a manner consistent with a coupled nonlinear oscillatory regime (Schmidt et al., 2011; Schmidt & Richardson, 2008). In our less-skilled group, this was clearly the case. When asked to coordinate in a complex competitive task that required synchronized coordination, our less-skilled participants behaved in a manner predictable by nonlinear oscillatory dynamics with signature lag/lead relationships that result from frequency detuning (Schmidt, Shaw & Turvey, 1993; Schmidt & Richardson, 2008). Specifically, when the attacker was weighted the defender led the dynamic and when the defender was weighted they lagged behind the attacker, and when no weights were added they were, on average, moving synchronously. However, as we expected, the more-skilled defenders assembled a strong dynamical coupling which allowed them, on average, to be able to maintain a consistently slight lead in the phase relationship between the interpersonal effectors we observed, in the x-dimension (anterior-posterior), despite the effects of load on either their own or their attackers' arms (see Figure 2). The imperturbable nature of the more-skilled defenders in maintaining the mean relative phase of interpersonal effector pairs across loaded conditions suggests this spatiotemporal parameter is a critical performance variable that is being maintained by this group. The mean relative phase of all interpersonal effector pairs of the more-skilled participants demonstrated that the defender was leading the overall interaction across all weight conditions in the x dimension. This suggests the defender was maintaining a competitive advantage by leading the spatiotemporal relationship even during the steady-state portion of the task before the take down, and perhaps in anticipation of the dynamics needed to cut the attacker's wrist and elbow down toward the ground. (As stated earlier, this final "take-down" movement in the experiment will be examined in a separate study).

While the x-dimension movement for this task was the primary dimension of action insofar as the two participants were approximately 1.5 meters apart from each other and had to cross that distance along the x-dimension to meet one another, the z-dimension was also important as the attacker was striking downward and the defender was parrying that strike by moving their arms upward. The mean relative phase of the effector pairs we observed in the z-dimension (superior-inferior) were generally less affected by weight for both skill groups. In the z-dimension, only the mean relative phase of the Wrist-Wrist (WW) interpersonal effector pair showed differences with weight and only in the less-skilled group (see Figure 3).

The WW effector pair demonstrated somewhat unique behavior compared with the other two interpersonal effector pairs in both mean relative phase as well as in the standard deviation of relative phase. In both groups, and in both dimensions, the WW effector pair was over twice as variable as the Sternum-Sternum (SS) and Wrist-Elbow (WE) effector pairs across all weight conditions. The relative consistency of the SS and WE effector pairs in terms of mean relative phase and lower levels of variability therein could suggest that these effector pairs were more critical interpersonal relationships that served the particular part of task we analyzed in this study.

In summary, while the less-skilled defender participants were able to raise their arms in the z-dimension with a similar phase lag across all weighted conditions, the lagging behind when the defender was weighted in the x-dimension and the leading too much when the attacker was weighted results in either meeting the attacker's arm too late (i.e. after the attacker has completed too much of their strike) or too early (i.e. waiting for the attacker's arm to arrive after the defender has already completed their movement). Interestingly, the mean relative phase of the SS marker pairs was unchanged across weight conditions in both skill groups. This suggests that all participants were coordinating their whole bodies somewhat similarly across loaded conditions. Therefore, the differentiation of skill in this task appears to reside in the more subtle movements of the participants' arms in relation to their partner's arms and more so in the x-dimension versus the z-dimension. This lack of difference in the SS effector pair is an important finding, as it clarifies the dimension and scale in which skill is emerging in this task. While everyone's sternums were largely being coordinated in a similar manner, the arms were clearly differentiated between skill groups.

Certainly, these observations are tempered by limitations of the study's methods. Our differentiation of skill levels into groups is imperfect. We used the rank of the martial artists to determine both their placement in comparable pairs and then to separate the pairs of participants into more and less-skilled groups. There is considerable variation in skill and experience even within these rank-matched pairs and across pairs within each skill group. For example, within our black-belt cohort we had ranks spanning first degree to fifth degree black belts, with experience *differences* within that group ranging in time spent training from a few months to over a decade. Additionally, a greater number of participants within each skilled group may have improved the power of our statistical analyses; however, the recruitment of skilled Aikido practitioners is relatively challenging and this, consequently, limited our study.

Stability and Flexibility in Skilled Coordination

The strength of the dynamical coupling in the more-skilled participant group was also reflected in the fact that they had lower amounts of relative phase variability overall. The less-skilled participants were consistently more variable than the more-skilled participants and did not show any differences in variability across the weighting conditions. Contrary to traditional expectations in the HKB model, the less-skilled participants showed changes in mean relative phase with detuning but not in their variability. Equally puzzling is that the variability of the more-skilled participants, while always lower than their less-skilled counterparts, was affected by frequency detuning, but mean relative phase was not impacted by weight. We observed significantly higher levels of variability in the more-skilled pairs, in the x-dimension, when either the attacker or defender was weighted and less variability in the non-weighted condition (see Figure 4). This dissociation between frequency detuning effects for mean relative phase and variability of relative phase has been reported before in coupled system coordination dynamics (Amazeen, et al., 1995; Richardson, et al., 2007) and been understood in terms of variability of the individual oscillators ($Q\zeta$) not being constant (counter to the assumptions of the HKB model) and 'percolating' up into the coordination patterns at the coupled level (i.e., relative phase). Richardson et al (2007) found this in a task where participants visually coordinated pendulum swinging with a rhythmically moving stimulus on a computer screen. In that study, increases in variability with frequency detuning were associated with noise ($Q\zeta$) rather than attractor strength. We speculate that the detuned ($\Delta\omega$) conditions in our experiment, where the limbs were weighted, resulted in increased noise ($Q\zeta$) independent of coupling strength (b/a), and that this noise may have its origin in the variability of the coordination at the intrapersonal level. It seems reasonable that the more-skilled participants may have been exploring different intrapersonal coordination strategies during the weighting conditions, perhaps in order to maintain critical spatiotemporal performance variables (i.e., getting their hands to the interception place just before the attacker does) that would increase their variability during these conditions. It also seems reasonable that the less-skilled participants may have lacked that flexibility in their intrapersonal coordination strategies (e.g., Figure 6), and as a result were too far behind the optimal timing when they were weighted and too far ahead of the optimal timing when their partner was weighted. Thus, the relative rigidity of the less-skilled participants' intrapersonal coordination may have led to an overall greater amount of interpersonal variability for them regardless of the weighting condition.

Consequently, the interpersonal variability results must be considered in the context of the intrapersonal coordination data. In the x-dimension, the more-skilled and less-skilled defenders had significantly different intrapersonal patterns of movement. The more-skilled defenders largely moved in-phase with a larger variance of movement centered around 0°, whereas the less-skilled defenders demonstrated a bimodal coordination strategy with most of their relative phase distributions centering around 0° but another clear anti-phase coordination pattern emerging around 180° (see Figure 5). Interestingly, the less-skilled defenders showed less variance in their intrapersonal coordination around these two coordination modes compared with their more-skilled counterparts' unimodal coordination strategy. This bimodal intrapersonal coordination strategy likely contributed to the overall higher levels of variability in the mean relative phase of our less-skilled interpersonal effector pairs. Additionally, the larger variability of the more-skilled defenders' intrapersonal coordination could reflect an effect of increased noise ($Q\zeta$) around a stable coordination pattern as a result of detuning as suggested above (Richardson, et al., 2007). The increased presence of anti-phase intrapersonal coordination for the more-skilled group when weighted (see Figure 6) is a potential source of this increased noise. While the significance and effect sizes of our intrapersonal region-weight-skill level interaction in the x-dimension was weak ($F(2.99, 68.78) = 2.22$, $p = .094$, $\eta_p^2 = .09$), we speculate that subtle differences between skill groups in their intrapersonal coordination could emerge as significant differences in their interpersonal coordination and warrants further study.

Variability has become synonymous with flexibility and agility in the literature on skilled movement (Seifert, Button, & Davids, 2013); however, our results also supported the repeated claims that too much variability (i.e., in our less-skilled participants) appears to relate to poor task performance (Chow et al., 2008). From a qualitative perspective, the difference in the performance of our less-skilled participants was markedly and visually different from our more-skilled participants. The speed, fluidity, consistency, and connectedness (both visually apparent and empirically measured) of the more-skilled participants were readily observable. The quality of directions provided by the instructional video that we showed to all of our participants would have had a more significant impact on our unskilled participants, who had never done any Aikido technique before. However, remarkably, we observed that all of the unskilled participants were able to approximate the technique after being shown the brief video and demonstrated strong whole body interpersonal coupling dynamics, as measured by the SS interpersonal effector pair. This suggests that gross social motor coordination is a powerful dynamical force that requires very little direction or practice in order to achieve, even in a complex task. However, skill may exist on a more subtle scale requiring considerably more practice and exposure, as was observed in the relative phasing of our more-skilled participants. Certainly, we could not possibly uncover all the subtle attributes of skill in this martial arts technique. We chose our pairs of effectors based our assessment of their relative importance in the coordination task. We admit that different interpersonal and/or intrapersonal effector pairs could be valuable to assess; however, our equipment limited us to a total of six markers.

Adaptations within Nested Intrapersonal Synergies Support Invariant Performance Outcomes

Interestingly, observed changes in interpersonal variability during weighted conditions for the more-skilled pairs may have been supported by changes in the way our more-skilled defenders managed their intrapersonal effector dynamics. We expected that the more-skilled group would show greater consistency within their intrapersonal coordination across weight conditions. Contrary to that expectation, the distribution of intrapersonal relative phase changed for the more-skilled group when they were weighted, exemplified in Figure 6 with the increased presence of anti-phase coordination for the more-skilled group when weighted. This increase in anti-phase coordination during the detuned conditions, which was nearly absent in the non-weighted condition, resulted in increased variability in the intrapersonal relative phase distribution with changes in weight for two of the three effector pairs for the more-skilled group. When either the attacker or defender was weighted, the more-skilled defenders demonstrated changes in their distributions of relative phase for the Defender Sternum–Right Wrist and Defender Left Wrist–Right Wrist; however, the Defender Sternum-Left Wrist distributions of relative phase remained unchanged across weighted conditions. The invariance across weight conditions in the Defender Sternum–Left Wrist effector pair for both relative phase distribution and variability therein could highlight the relative importance of that effector pair in the performance of this task.

The relative stability of one intrapersonal effector pair and the increased variability of the other two effector pairs implies that the attention of the defenders may have been highly focused on a very limited number of variables. This suggests that the intrapersonal synergies assembled within the defender are organized around a more precise task objective, perhaps aimed at reducing the number of degrees of freedom to control. In our task, that would appear to be the spatiotemporal connection of the Defender Sternum–Left Wrist intrapersonal synergy (Figure 5) nested within and supporting the Defender Left Wrist–Attacker Elbow interpersonal synergy. The other effector pairs, while important and necessary in the overall task space, may be subjugated and thus allowed to become more variable in their coordination evidenced by the higher rates of variability for the more-skilled group of the mean relative phase of the other interpersonal (Wrist-Wrist) and intrapersonal synergies (Defender Sternum–Right Wrist and Defender Left Wrist–Right Wrist). Alternatively, some intrapersonal effector pairs switched their lag-lead relationships when weighted, perhaps because of the importance of getting that effector moving toward its target. Specifically, in the Defender Sternum–Right Wrist, when weighted, the defender moved that wrist ahead of the sternum, which was unique to the other weight conditions.

Given that the Defender Right Wrist was the effector that was intercepting the attacker's wrist (the hand that was about to hit the defender), we may have been observing a prioritization of that effector moving in advance of the whole body. Either way, we saw that the more-skilled participants were manipulating their intrapersonal movement strategies while maintaining an invariant interpersonal coordination goal.

The absence of changes in intrapersonal coordination across all effector pairs with weight for the less-skilled participants (see Figure 6) could suggest rigidity in their coordination resulting in a lack of ability to respond to changing environmental circumstances. However, it is important to note that the less-skilled participants were consistently more variable in their intrapersonal relative phase distributions across all weight conditions compared to their more-skilled counterparts, as we expected. Nevertheless, the significant changes in the mean relative phase of the interpersonal coordination that resulted from the changing weight conditions for the less-skilled participants may be founded upon this observed lack of intrapersonal coordination agility. In other words, it is possible that the less-skilled participants were unable to manipulate underlying nested intrapersonal synergies in service of the interpersonal task objective.

Task Demands Dominate Passive Dynamics in a Skilled Competitive Task

The concerted effort to maintain an invariant task performance, despite perturbation, and the use of a flexible coordination strategy has been echoed in previous literature on skilled movement (Black et al., 2007); however, the present study is a relatively unique contribution to the literature on dyadic competitive tasks. Our more-skilled participants defied the frequency detuning of passive oscillatory dynamics by maintaining critical performance variables (i.e. mean relative phase) when weighted. To this end, the more-skilled participants allowed increases in variability (i.e. flexibility) both within the interpersonal and intrapersonal task space, perhaps as a deliberate strategy to prioritize more task-critical goals (i.e. relative phase of Defender Wrist-Attacker Elbow effector pair).

In our previous study utilizing a paired sword-swinging task (Schmidt et al., 2011), we observed that weight impacted both skilled and unskilled groups; however, it affected the mean relative phase of interpersonal effectors less in the skilled group. In the current study, we observed that weight had no impact on mean relative phase of the more-skilled group in any of the effector pairs we observed. This remarkable invariance across all effector pairs and all weighted conditions suggests that the competitive task dynamics in the present study were substantially different than our more cooperative synchronization tasks in that previous research. As we seek to apply a theory of social coordination to more competitive sports tasks, our study suggests that skill development may involve some level of exploitation of and deviation away from passive dynamics of coupled nonlinear oscillators to maintain or take some advantage in the interpersonal relationship. It is perhaps necessary for the more-skilled actors to sense that they are or would be leading/lagging in the interpersonal task space; thus, prompting some tuning of either their biomechanical parameters (i.e. stiffness) or spatiotemporal parameters (i.e. intrapersonal effector coordination) to maintain the critical performance variable dictated by the task.

Conclusion

Our study lends considerable support to the advancing literature on social motor coordination that uses an ecological framework in conjunction with dynamical systems theory to better understand how people coordinate with each other in a shared task space and furthers the literature on understanding interpersonal coordination and skill, particularly in competitive sports. In particular, our observation that the more-skilled participants generally used a more flexible intrapersonal coordination strategy while achieving an invariant interpersonal relationship among multiple effector pairs lends support to the multidimensional nature of nested synergies in an interpersonal coordination task (Schmidt & Richardson, 2008; Black et al., 2007). While our study supports the existence of nested synergies and the use of variability within them to achieve a task objective, further research is needed to understand how variability at the intrapersonal level is impacting task performance in complex interpersonal coordination tasks. Our study also raised the question of prioritization and subjugation among synergies in a complex task. Herein, our skilled participants demonstrated remarkable invariance within a very limited set of nested interpersonal-intrapersonal synergies, while apparently utilizing increased variability within other synergies to maintain the overall task objective. Of course, additional research is needed to replicate and confirm the existence of prioritized and subjugated synergies in bimanual asymmetric tasks. Our chosen task was uniquely complex in the literature and bimanually asymmetrical, which may have enabled (or forced) these differing synergistic strategies. Nevertheless, it appears that skilled coordination in a competitive sports task involves some adaptation of the dynamics of the coupled nonlinear oscillatory regime we have repeatedly observed in more cooperative tasks.

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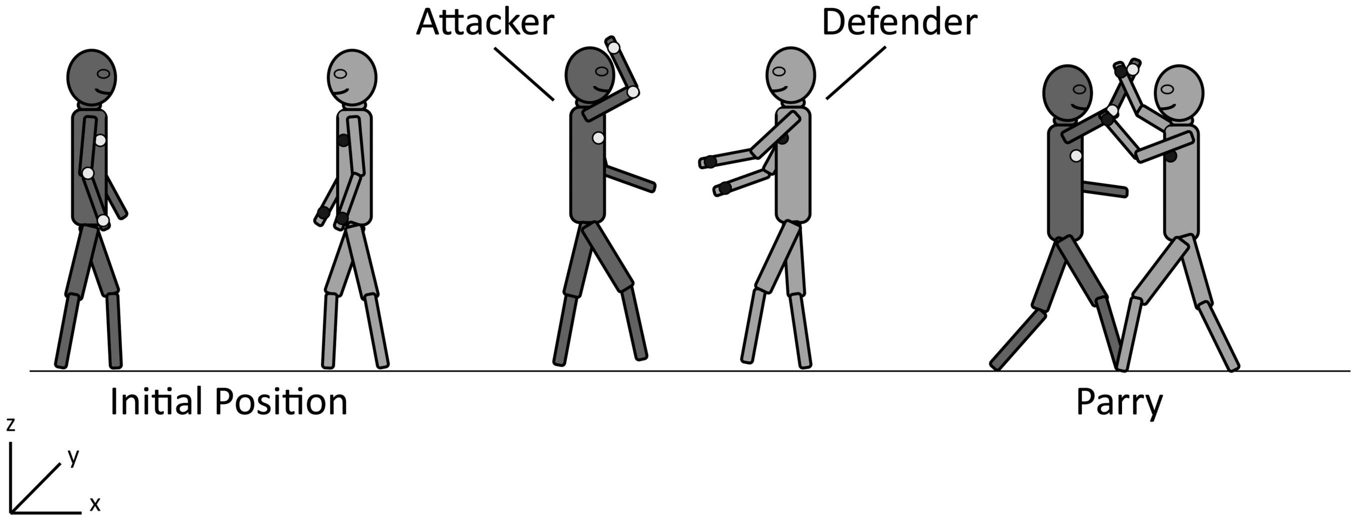

Figure 1.

The portion of the technique analyzed herein involves the Attacker performing an overhead strike toward the Defender's forehead with their right arm. The Defender parries the strike using both of their arms with the Defender's left wrist meeting the Attacker's right elbow and the Defender's right wrist meeting the Attacker's right wrist. The x-dimension is anterior-posterior, and the z-dimension is superior-inferior. The interpersonal task generally produced more anti-phase ($\phi = 180°$) coordination in the x-dimension and more in-phase ($\phi = 0°$) coordination in the z-dimension.

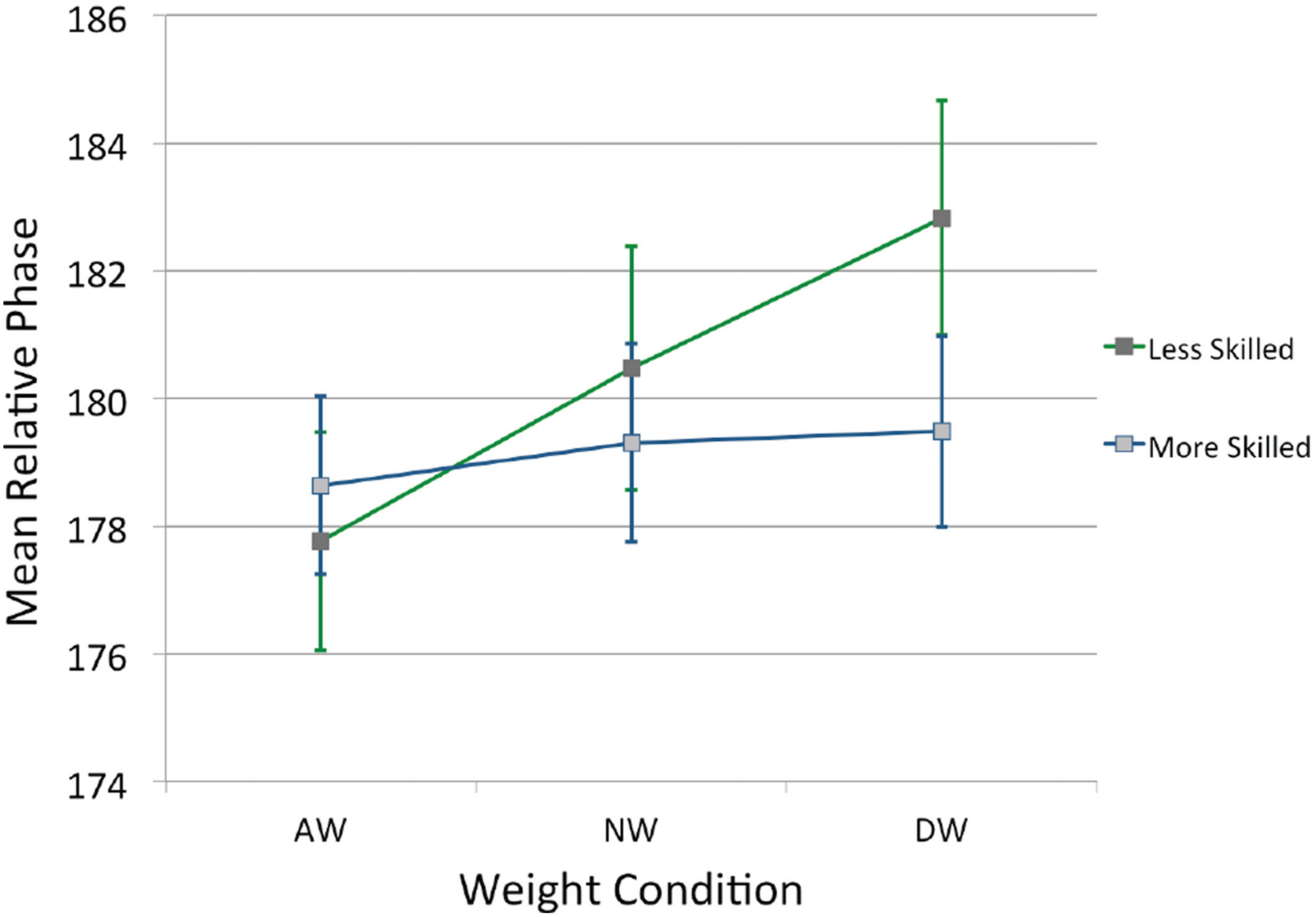

Figure 2.

Mean relative phase (RP) of all effector pairs combined in the x-dimension for the more-skilled group is unchanged; whereas, the less-skilled group demonstrates a predictable lag-lead relationship in RP across weight conditions.

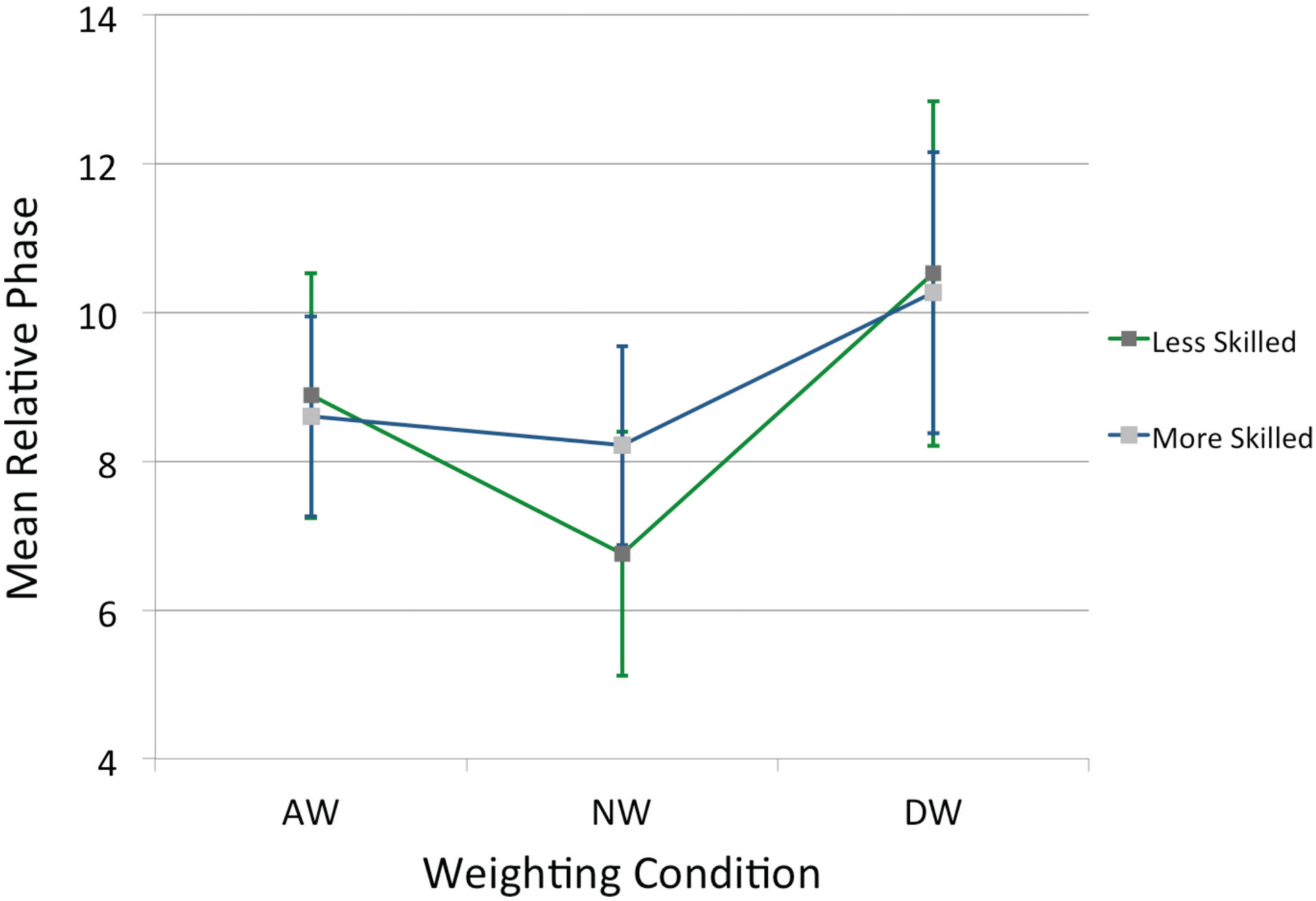

Figure 3.

The effect of weight on RP of the WW effector pair in the z-dimension with skill groups plotted separately. Only the less-skilled group differed significantly in RP between the NW and DW conditions.

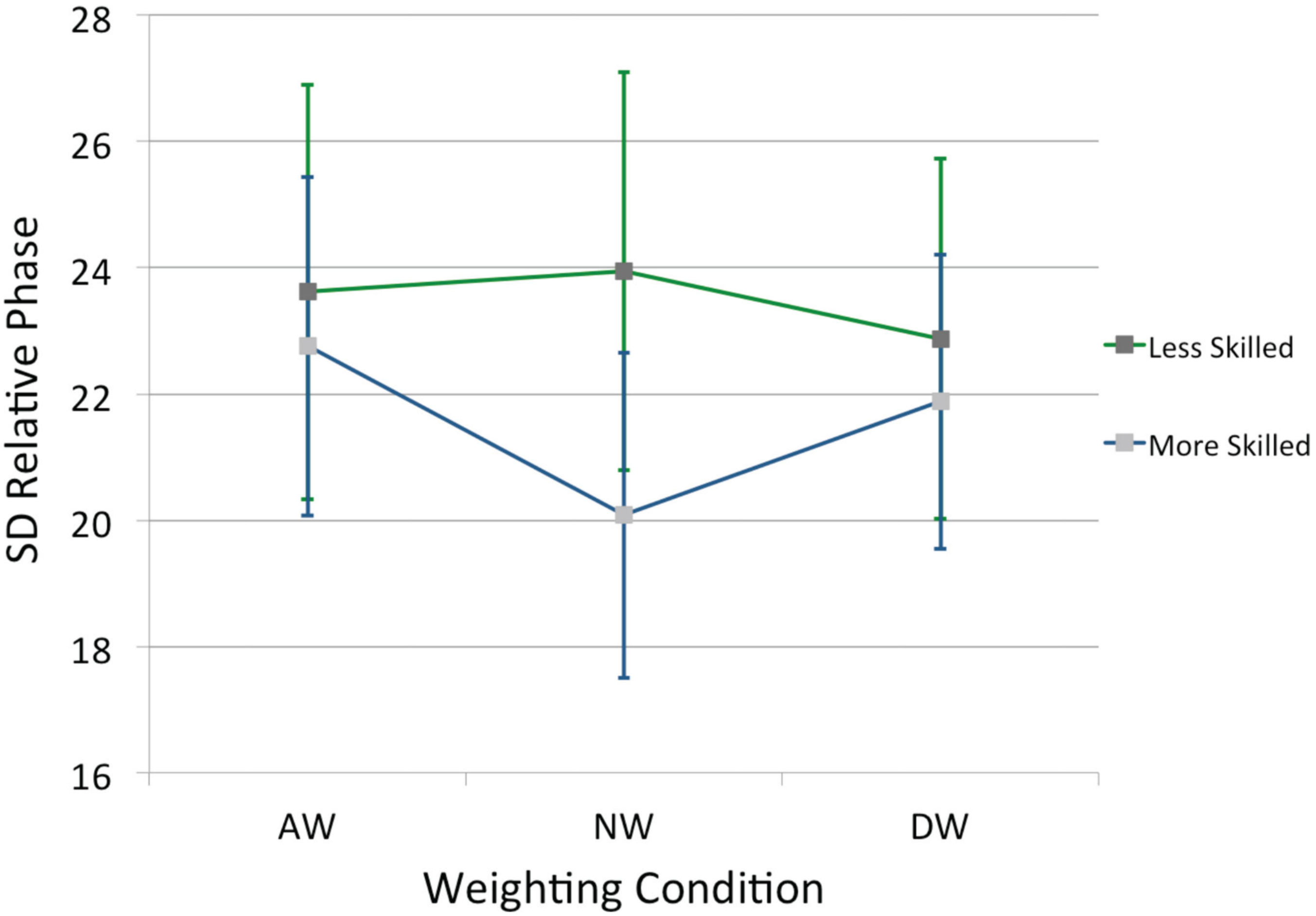

Figure 4.

Mean standard deviation of relative phase (SDRP) for all effector pairs was unchanged in the x-dimension, but on average higher, for the less-skilled group. During the NW condition the more-skilled group was significantly less variable than during the AW condition and slightly less variable than during the DW condition.

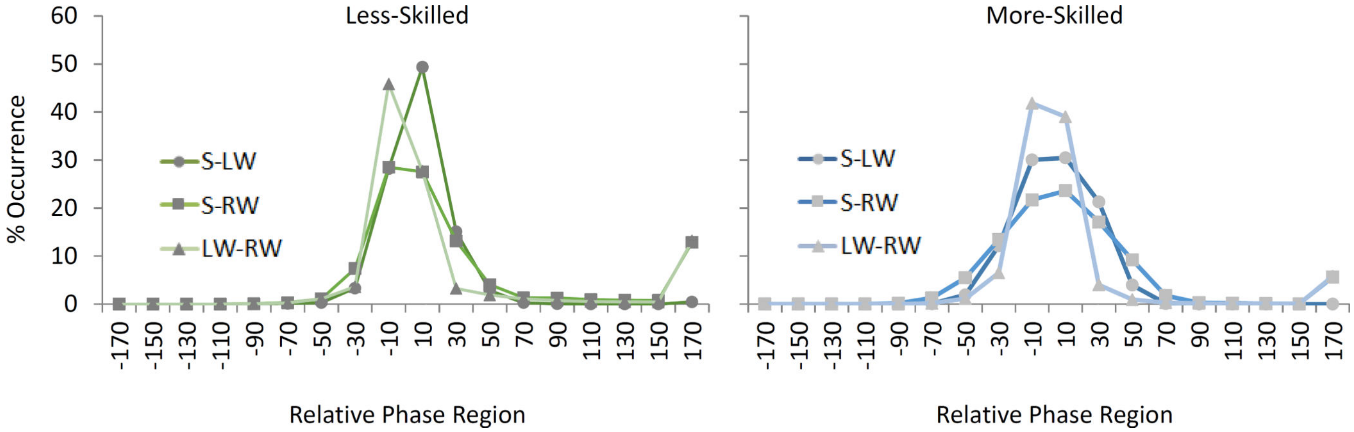

Figure 5.

The percentage of observations within each of the 18 phase regions (from −180° to 180°) as a function of the three intrapersonal effector pairs (Sternum-Left Wrist [S-LW], Sternum-Right Wrist [S-RW], Left Wrist-Right Wrist [LW-RW]) for both the less- (left panel) and more-skilled (right panel) groups of defenders in the x-dimension.

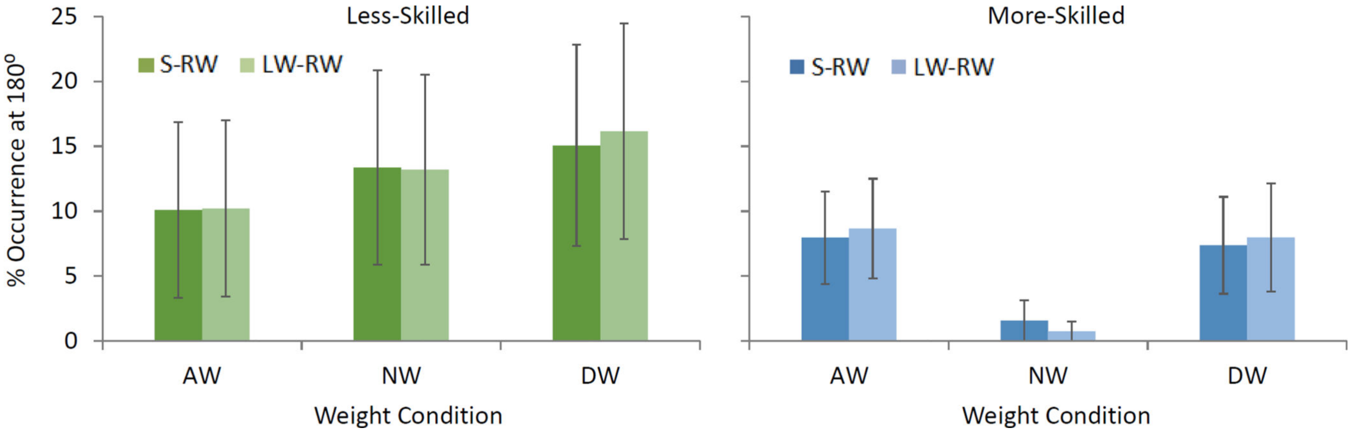

Figure 6.

The percentage of observations within the 180° phase region as a function of the weight condition (Attacker Weighted [AW], Non-Weighted [NW], and Defender Weighted [DW]) for the Sternum-Right Wrist (S-RW) and Left Wrist-Right Wrist (LW-RW) effector pairs for both the less- (left panel) and more-skilled (right panel) groups of defenders in the x-dimension.

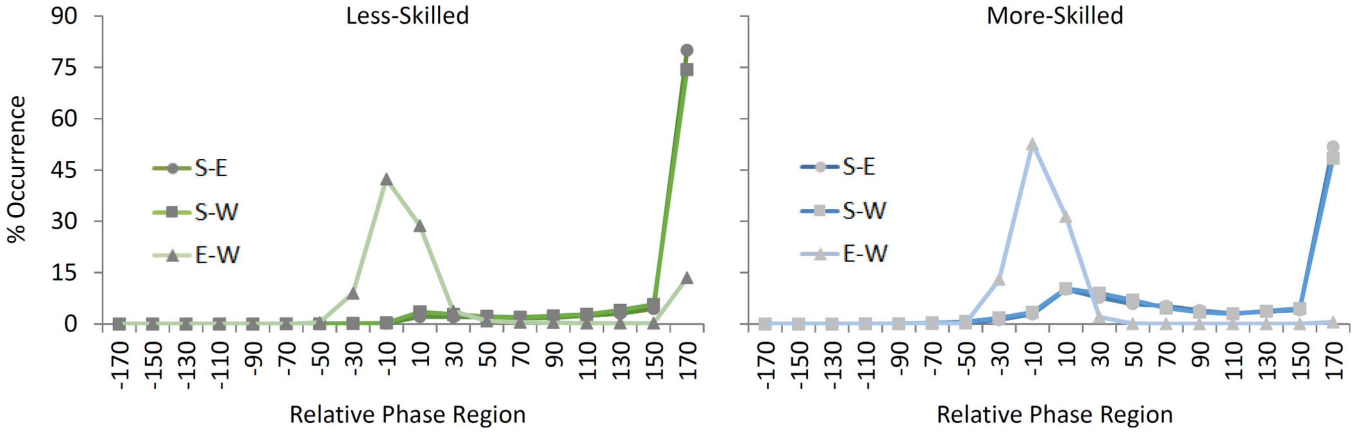

Figure 7.

The percentage of observations within each of the 18 phase regions (from −180° to 180°) as a function of the three intrapersonal effector pairs (Sternum-Elbow [S-E], Sternum-Wrist [S-W], Elbow-Wrist [E-W]) for both the less- (left panel) and more-skilled (right panel) groups of attackers in the z-dimension.