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Michael D. Iott
The University of Toledo

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Michael D. Iott

Research Advisor: Martin S. Rice, Ph.D., OTR/L

Occupational Therapy Doctorate Program

Department of Rehabilitation Sciences

The University of Toledo

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Abstract

Interlimb coupling is the synchronicity and symmetry that the body tries to achieve between limbs as they move simultaneously and it causes individuals to have a difficult time producing different movements simultaneously even if the individual movements are not difficult in nature. In this study, researchers assessed the degree of interlimb coupling at the shoulder joints and the wrist joints in 29 healthy adults by having the participants match the cadence of a metronome with a decoupled, oscillatory movement pattern. The study consisted of two, two-minute trials in which the participants oscillated at the shoulders for one trial and the wrist for the second trial. As the trials progressed, the metronome increased in speed making it more difficult to maintain a decoupled movement pattern. A comparison between the degree of interlimb coupling at these joints during slow cadences and fast cadences was completed to determine whether or not there was a difference in the degree of coupling throughout the trial. The results indicate that there is not a statistically significant difference between the amount of coupling in the shoulders and wrists during the slow oscillations (F=0.002, p=0.963). However, as the metronome increased in speed and the task became more difficult; the results demonstrate that there was a statistically significant difference in the degree of interlimb coupling between the shoulder and wrist joints (F=5.395, p=0.028). More specifically, the wrist joint was more capable of maintaining a decoupled movement pattern during the faster cadences than the shoulder joint. Future research should continue to examine the degree of interlimb coupling at the various joints of the upper extremity, should assess how these dynamics affect movement patterns during everyday occupations, and should be extended to stroke populations.

Keywords: Interlimb coupling, bilateral coordination, bilateral movement, bimanual coordination, upper-extremity movement, movement synergy.

Interlimb Coupling in the Proximal and Distal Joints: A Comparison

Interlimb coupling is regarded as a fundamental aspect of the neuromotor system organization (Harris-Love, Waller, and Whitall, 2005). Interlimb coupling is the synchronicity and symmetry that the body tries to achieve between limbs as they move simultaneously. The limbs, especially the upper extremities, often have a difficult time performing different tasks at the same time even if the individual tasks are not difficult in nature (e.g., making a circular motion in one arm while trying to flap the other arm as if trying to fly). A number of researchers found that symmetrical coordination patterns between limbs associated with concurrent timing of the necessary muscle groups in each limb (in-phase) are performed with higher accuracy, stability, and in some cases, speed in comparison to movements that are asymmetrical and involve alternating activations of the muscle groups needed for the action (Rice and Newell, 2004; Rice and Newell, 2001; Kelso, Southard, & Goodman, 1979a, 1979b; Sugden and Utley, 1995). These results can be extended beyond the general, healthy population and into the realm of individuals with disabilities.

In healthy populations, a bilateral attraction occurs when moving both upper extremities at the same time in a synchronous fashion. The types of bilateral movements where synchrony can occur are typically those where the movements in one limb are in some sort of harmony with the movements in the other limb. Such limb movements occur in a coordinated manner and can range from where each limb mirrors the movement of the other to where the movements are asymmetrical, but are still anchored to each other usually in a rhythmic fashion. Interlimb synchrony is considered to be a more economical movement pattern than interlimb asynchrony. Interlimb synchrony occurs when the two limbs move in a 1-to-1 pattern, also referred to as an in-phase pattern. An in-phase movement pattern can be defined as the simultaneous activation of homologous muscles or muscle groups (Dessing, Daffertshofer, Peper, and Beek, 2007). An example of this would be simultaneously flexing at the elbow with each arm at the same time. This synchronous movement has been found to be the preferred rate of bilateral movement and recent research suggests it can result in significant, functional gains in chronic hemiparetic patients (Whitall, Waller, Silver, and Macko, 2000; Mudie and Matyas, 2000). The 2:1 pattern, or anti-phase movement pattern consists of one limb completing one action while the other limb produces two of the same action, in the same time requirement. For example, when referring to oscillations at the shoulder, the right shoulder completes one complete oscillation while the left completes two complete oscillations in the exact same amount of time.

The concept of interlimb coupling has a variety of applications pertinent to healthy and unhealthy populations. Rice and Newell (2001) compared individuals who had left hemiplegia to healthy individuals in terms of interlimb coupling. The participants established a preferred rate of oscillation for each upper extremity, and then a preferred bilateral rate of oscillation. The preferred rate of oscillation can be described as the most comfortable rate and amplitude at which the participant flexed and extended at the elbow within a natural range of movement. The researchers then discovered that the individuals with hemiplegia displayed a frequency of oscillation and peak velocity in the affected limb that was more similar to the frequency and velocity of the bilateral movement than the unaffected limb. The unaffected limb showed significant differences between the unilateral and bilateral conditions suggesting that the unaffected limb was limited by the slower, affected limb. During the bilateral movement, the affected limb appears to use more effort to match the movement of the unaffected limb, and this causes it to “drive” the movement dynamics throughout the bilateral condition (Rice and Newell, 2001). In simpler terms, the affected limb constrains the capabilities of the unaffected limb by causing the unaffected limb to conform its movement to the pattern of the affected limb.

Furthermore, the synchronous movement pattern has been seen to be a more stable condition than the 2:1 pattern for individuals with left hemiplegia (Rice and Newell, 2004). Researchers compared the oscillatory movement patterns of participants with left hemiplegia due to cerebrovascular accident (CVA) to a control group. The oscillatory patterns consisted of two asymmetric conditions which were right-fast-left-slow (RFLS) and left-fast-right-slow (LFRS). In the RFLS condition, the right limb oscillated at a 2-to-1 ratio while the left limb oscillated at a 1-to-1 ratio while it was the opposite during the LFRS condition. The oscillatory movement consisted of flexing and extending at the elbow joint to metronome guidance. The hemiplegic participants demonstrated great difficulty when attempting to settle into a less stable, 2:1 pattern and were therefore bound to a more stable, in-phase, interlimb coupling movement pattern. In contrast, the control group produced a variety of movement patterns including antiphase, in-phase, and the 2-to-1 movement pattern. Therefore, Rice and Newell (2004) found that participants with hemiplegia due to cerebrovascular accident (CVA) were generally limited to an in-phase, 1-to-1 movement pattern.

Also, Harris-love, Waller, and Whitall (2005) found that interlimb coupling effects were seen in subjects with hemiparesis caused by stroke. In their study, they asked 32 subjects with chronic unilateral ischemic stroke to reach to the side of a box placed on a table in front of their seat. There were three conditions of the independent variable: reach with non-paretic arm, reach with paretic arm, and bilateral reach. They documented that bilateral tasks allowed the paretic arm to achieve higher velocity and acceleration peaks. They also demonstrated that movement time in the non-paretic arm was significantly increased during a bilateral task indicating a drive towards synchrony, or interlimb coupling. These findings suggest that utilizing interlimb coupling during treatment sessions will immediately improve the movement performance of the paretic arm.

The effects of interlimb coupling were also found in individuals with cerebral palsy (Langan, Doyle, Hurvitz, and Brown, 2010; Hung, Charles and Gordon, 2004; Utley and Sugden, 1998; Utley and Sugden, 1995). A study by Utley and Sugden (1998) utilizing 11 children with hemiplegic cerebral palsy examined the reaching and grasping dynamics using 3D kinematic analysis and video recordings. The reaching and grasping speed was studied while the children engaged in one of the three conditions: reach and touch object at speed, reach and grasp object at speed, and reach, touch, and grasp. Utley and Sugden (1998) found that increased speed facilitated the coupling effects which were stronger during the first part of the movement. These researchers suggested teaching individuals with cerebral palsy to move at higher speeds, bilaterally because it will decrease the number of movement difficulties they may have when moving unilaterally.

Lastly, research has also shown that bilateral movements are only as fast as their slowest component. In a set of three classic experiments, Kelso, Southard, and Goodman (1979a, 1979b), used high-speed cinematography (200 frames per second) to analyze the coupling effects between the two upper extremities. In Experiment 1, upon hearing the stimulus to move, the subjects lifted their index fingers off the home keys which were positioned directly in front of them and moved them to the target(s) depending on the demands of the condition. Using reaction time data, they showed that the subjects initiated and terminated the two-handed movements simultaneously. These results were found despite the subject having independent task demands for each arm in some bilateral conditions. In the second experiment, the apparatus was set up similarly, except that the targets were located directly in front of the participants while the home keys were positioned at varying locations throughout the experiment. Once more, the two handed movements with equal difficulty had execution times that suggested simultaneity. It was apparent from their results that the more difficult task determined the overall movement time throughout the two-handed conditions. In the third experiment, the set-up was altered so that the subjects could make movements forward in the sagittal plane instead of laterally like they had in the previous two experiments. Just as in the previous two experiments, the subjects initiated the bilateral movements together and the more difficult task influenced the movement time of both limbs, including the limb engaging in the easy task. In summation, they displayed that individuals engaging in an asymmetrical task condition recorded movement times that were determined by the arm engaging in the more difficult task.

Von Holst (1937/1973) gave terms to the tendencies he witnessed in the movement patterns of oscillators, such as the two limbs of an organism. One characteristic movement pattern consisted of the "maintenance tendency." This involved the tendency of one limb to oscillate at a steady, 1:1 frequency while being "locked in" with the movement of the other limb (von Holst, 1937/1973). Another term he coined was the "magnet effect" which occurs when one oscillator becomes influenced by the patterns of the other, contralateral oscillator. Hence, von Holst stated that one oscillator attempted to oscillate at its own preferred rate, all-the-while influencing the oscillation tendency of the other oscillator. In addition, Von Holst termed "Absolute Coordination," to describe the situation where two oscillators or limbs are "locked in" at the same frequency, and is the result of the interaction between the magnet effect and the maintenance tendency (von Holst, 1937/1973).

More recently, Gilbert, Isaacs, Augusta, MacNeil, and Mostofsky (2011) explored the possibility that transcranial magnetic stimulation (TMS) evoked measures within the motor cortex are related to the childhood severity of attention deficit hyperactivity disorder (ADHD) and the motor delays typically seen in children. The task involved a unilateral, one-handed finger-tapping test with the independent variable being the excessive movement in the opposite hand. Interestingly, they discovered that the participants with ADHD had their short interval cortical inhibition (SICI) reduced by approximately 40% and this lowered inhibition was correlated with more severe cases of ADHD. The participants' inability to inhibit also reflects delays in motor control, especially during repetitive and sequential movements.

Moreover, additional research utilized a qualitative approach to discover that phasic overflow and total overflow in both hands were greater in children with ADHD than in the control children (Macneil, Xavier, Garvey, Gilbert, Ranta, Denckla, & Mostofsky, 2011). The motor overflow, or "mirroring," was more prominent in the nondominant hand, while the children engaged in the task. Researchers also indicated that there are gender-based differences demonstrating that boys with ADHD show significantly more total phasic overflow and total overflow than the gender-matched, control children. These studies provide valuable information to those studying bilateral movement or interlimb coupling. They suggest that the mechanisms needed to inhibit the actions of one limb are less active in those with ADHD causing "mirroring" movements. One can think of movement and action as a series of turning on and off signals from the brain. If an individual has a disorder or suffers an injury that impairs their ability to regulate these signals, movement can potentially be altered.

Dounskaia, Nogueira, Swinnen, and Drummond (2010) surmised that the effects seen between limbs have more to do with the obstructive forces of the dominant arm's interaction torque used during symmetrical and asymmetrical movements. These researchers recruited 13 healthy, right-handed individuals and asked them to use their index fingertips to draw circles around a designated center point. They used two patterns of bimanual coordination, symmetrical and asymmetrical. The symmetrical coordination pattern involved the individuals using a clockwise motion with the non-dominant hand and a counterclockwise motion with the dominant hand. The asymmetrical coordination pattern involved both limbs using a clockwise motion. The results of their studies supported two bimanual tendencies. The first, a well-known and well-supported idea (Kelso et al., 1979; Kelso, 1984; Peper and Beek, 1999; Rice and Newell, 2004), suggests that there is a shift toward symmetrical coordination when nonsymmetrical upper limb movement is occurring. The second tendency revealed that there is a destabilization of symmetrical coordination as movement speed increases. This destabilization occurred due to a tendency of the separate arms to produce different movements. According to the researchers, there was inefficient control over the interaction torque of the non-dominant hand causing trajectory differences and altered shapes as the speed of the movement increased.

An important concept proposed by previous research is that the tendency for mirror symmetry occurs due to simultaneous activation of homologous muscle groups during bilateral movements (Kelso, 1984; Peper and Beek, 1999; Byblow et al., 1992; Riek et al., 1992; Serrien and Swinnen, 1998; Swinnen et al., 1992, 1998). Symmetrical movements result most often because the neural circuits promote the simultaneous transmission of movement commands to the same muscles in each limb. Therefore, nonsymmetrical movements must require additional effort to inhibit the bilateral message being sent to activate the muscles of each limb. They then infer that one’s inter-arm differences may be attributable to handedness and the differences between the dominant and non-dominant upper extremities (Dounskaia et al., 2010).

In addition to the previously stated studies, Li et al. (2005) conducted research to examine the interactions between interlimb and intralimb coordination during bimanual, multi-joint movements. The researchers recruited 13 healthy participants to perform eight tasks involving the wrists and elbows of both extremities under a series of different coordination conditions. Interlimb coordination involved in-phase and anti-phase (opposite movements occurring at different joints) coordination patterns while intralimb coordination methods employed isodirectional and non-isodirectional patterns. The isodirectional mode involved simultaneous flexions and extensions in the wrist and elbow joints of the same arm. In contrast, the non-isodirectional mode consisted of flexion in one joint while simultaneously extending in the other, or vice versa.

Li et al. (2005) had three major findings, the most significant of which was that multi-joint movements involving simultaneous activation of the same muscle groups in each arm in-phase were completed with higher accuracy and consistency. This finding was suggested due to the higher relative phase accuracy and lower variability between limbs while the wrists were in the in-phase mode. Another important discovery was one related to intralimb coordination. They found that isodirectional coordination resulted in a higher quality and higher stability of intralimb coordination than the non-isodirectional mode. They noticed that this effect was especially evident in the dominant limb. Lastly, they found that the mode of interlimb coordination affected the quality of the intralimb coordination more so than the intralimb coordination affected interlimb coordination. For example, anti-phase interlimb coordination patterns in the distal joints resulted in lower accuracy and stability of intralimb movements. The researchers surmised that there exists a hierarchical control structure in which interlimb coordination constraints supersede intralimb coordination constraints. The research conducted by Li et al. (2005) is also unique in that it suggests that the distal joints in the upper extremities exhibit a more powerful impact on the quality of multi-joint coordination than the proximal joints.

The neuroanatomy underlying the motor patterns involved in upper extremity action are very complicated and will therefore be simplified in this section. Lundy-Ekman (2007) states that the primary motor cortex (PMC) is located in the precentral gyrus, just anterior to the central sulcus. It receives projections from several areas including the secondary and tertiary motor areas and the supplemental motor area (SMA). The corticospinal tract originates in this area and primarily controls the voluntary, contralateral movements of the hand and face. These axons project caudally, first passing through the internal capsule, then the cerebral peduncles, from there the internal capsule, the pyramids of the medulla, and finally the lateral spinal cord where they synapse with the lower motor neurons controlling fine distal movements. In the lower medulla, where the medulla meets the spinal cord, the lateral corticospinal axons decussate to the contralateral side while the medial corticospinal axons remain ipsilateral. The lateral corticospinal tract is pertinent to the fractionation, the ability to move individual muscles independently of other muscles in the same areas, of the movements of distal muscles (Lundy-Ekman, 2007). Therefore, it is important to mention that there are different corticospinal tracts dedicated to the proximal and distal joints of the upper extremity.

The corticospinal cell bodies located in the PMC are arranged somatotopically where areas with more neuronal representation, such as distal extremities, are indicated by more representation in the PMC, meaning a larger portion of the PMC is dedicated to them. This somatotopic representation is referred to as a homunculus. On the homunculus, the distal portions of the upper extremity have more cortical representation in the brain than the proximal portions. The increased amount of cortical representation is what gives the hands more fine dexterity than the other, more proximal joints (Martini, 2005).

As mentioned earlier, the SMA is an important area for movement. Located just anterior to the lower body region of the PMC, this area is essential for the initiation of movement, orientation of the eyes and head, and planning bimanual and sequential actions (Lunky-Ekman, 2007). This area is also fascinating because 5 to 7% of the projections from the SMA affect the ipsilateral side. Stimulation of the supplementary cortex cells is seen during movements that require bilateral coordination of the upper extremities such as tying a shoe and sequential movements such as putting a shirt on before putting a coat on. Besides the SMA projections, nearly 25% of the PMC projections remain ipsilateral and merge with the CST thereby influencing the ipsilateral side. Combined, these two respective areas and their projections are thought to be the important factors contributing to interlimb phenomena.

There are several factors that can affect the proper functioning of the previously discussed neural pathways. Cerebral vascular accidents (CVA), or strokes are the leading cause of adult disability and a very commonly occurring event that can cause a disruption in the normal functioning of the neural pathways (Whitall, Waller, Silver, and Macko, 2011). Each year, approximately 750,000 Americans suffer from a stroke and it is estimated that approximately 5.4 million Americans are living with the lingering effects of a stroke (National Stroke Association, 2009). A stroke occurs when an area of the brain has its blood supply significantly reduced, or stopped, thereby causing a lesion in the brain tissue supplied by the affected source. The lesion(s) can alter the ability of that area of the brain to operate or transmit signals properly leading to decreased or altered function in various areas of the body. It is possible that the damage can affect all functions of the body, but most commonly, stroke results in hemiparesis, hemiplegia, and speech and language disorders (National Stroke Association, 2009). Hemiparesis, the weakness of one side of the body and hemiplegia, the paralysis of one side of the body are the two symptoms that would significantly benefit from interlimb coupling (Rice and Newell, 2001; Rice and Newell, 2004; and Harris-Love et al., 2005).

The concept of interlimb coupling has very important implications for rehabilitation therapy practices, especially those pertaining to occupational therapy. Occupational therapy emphasizes engaging the patient in meaningful and purposeful occupations to achieve improvements in functioning and quality of life. It is without question, that finding effective ways to improve function and precision in affected upper extremities is of the utmost importance for a number of populations including stroke victims, individuals with cerebral palsy, and those who have suffered a traumatic brain injury. Therefore, the goal of this research is to add to the body of knowledge regarding interlimb coupling, more specifically, interlimb coupling at both proximal and distal joints of the upper extremity.

The relationship between the location of the joint, proximal or distal, and the amount of strength at which the coupling forces occur has yet to be established. Having an understanding of the magnitude of coordination at the various joints in the arm will help therapists establish evidence-based, bilateral treatment plans for those with weakness or paralysis in an upper extremity. Furthermore, knowing the tendencies of interlimb coupling present at the joint being treated, will also suggest what other movements may be occurring proximally or distally to the relevant joint and how these movements may influence movement throughout the extremity. Overall, the hope for this research is that increasing the knowledge of interlimb coupling will help therapists create efficacious treatment sessions focused on improving the bilateral motor control needed to complete activities of daily living (ADL’s).

The purpose of this study is to investigate the differences in interlimb coupling patterns at the proximal and distal joints of the upper extremity during oscillatory movement. Based on previous research presented by Li et al. (2005), we hypothesize that the proximal joint will be more coupled than the distal joint thereby allowing the distal joints to be more capable of decoupling.

Method

Participants

Thirty-two healthy, male and female adults from the Midwestern United States were recruited to participate in this study. The sample included 26 females and six males and the mean age of the participants was 24.38 years (SD=2.49). Due to problems with data collection, three of the participants' data were discarded leaving the researchers with a sample size of 29 (n=29). These individuals were both right and left hand dominant. They were recruited via recruitment flyers and word of mouth. Therefore, all of those who participated were volunteers making the participants a sample of convenience. The inclusion criteria involved having no neuromuscular or physical impairment that would adversely affect their ability to perform active range of motion exercises in the upper extremities. Specifically, participants were required to have at least 120 degrees of shoulder flexion, 120 degrees of elbow flexion and the ability to accomplish circumduction freely at the wrist and functional use of both hands. Exclusion criteria included presentation of pain in any of the joints in the upper extremity, limitations in upper extremity joint range of motion; specifically having < 120 shoulder flexion and < 120 degrees of elbow flexion.

Apparatus

A 3-D Qualysis motion capture system using 4 ProReflex cameras was used to capture the movements of the two upper extremities. A metronome customized from the Audacity 1.3 Beta Program was utilized to aid in the pace-setting movement for the participants.

Design

This study used a counterbalanced, repeated measures design involving two conditions: one that focused on shoulder oscillations while the other focused on wrist oscillations.

Procedure

This research study was approved by The University of Toledo Biomedical IRB. Data were collected from September through December 2011. Informed consent was obtained from each participant prior data collection. After providing consent, the participants were randomly assigned to one of two treatment orders. Participants' upper extremity active range of motion (AROM) was screened using an upper AROM screening assessment (i.e., participants were asked to raise their arms above their shoulders, flex their elbows, supinate, pronate, flex, and extend their wrists and open and close their fingers). Participants were also asked if they were currently experiencing any pain in their upper extremities. If pain was present or there were any limitations in their AROM, then they would have been excused from the study. Fortunately, there were not any participants that were experiencing these problems.

Reflective markers were placed bilaterally on the participant's shoulders, triceps, elbows, forearms, wrists, and metacarpophalangeal (MCP) joints of the third finger. The participants also wore a headband with a reflective marker attached to the front of it as a reference point. Once again, the participants were randomized to one of two condition orders; shoulder oscillation first, and wrist oscillations second or the opposite. In the shoulder oscillation condition, the participants were moving their arms in an oscillatory motion using the shoulder joints while in 90 degrees of shoulder flexion. They oscillated at the shoulder while extended at the elbow for a period of two minutes. Verbal prompts were provided to ensure that the participants' elbows remained extended throughout the condition. This motion was meant to be localized to the shoulder joint. Also, the participants were told that there was thirty seconds left after a minute and a half of the trial had been completed. After a 2-minute period of rest, the participants performed an oscillatory motion at the wrist joint instead of the shoulder while the elbow joint was extended to approximately 180 degrees and the shoulder were flexed to 90 degrees. In both conditions, participants were instructed to oscillate their limbs while matching the cadence of a metronome. Simply put, in the ‘shoulder’ condition, participants exclusively oscillated their upper extremities at the shoulder joints and in the ‘wrist’ condition, participants oscillated exclusively at the wrist; otherwise the two conditions were identical. The participants were given a laser pointer to hold in each hand. On the wall in front of their seats were two circles of equal size that they attempted to trace using the laser pointers. This provided the participants with visual feedback throughout the trials.

The metronome sounded at an increasing pace and was utilized as a guide to help the participants coordinate their movement. In other words, as the trial proceeded, the rate of the metronome increased. The metronome began with a 1 second cadence and increased to a .2 second cadence across a 2 minute period. The cadence progressed from 60 beats per minute (bpm) to 80 bpm, 100 bpm, 120 bpm, 140 bpm, 160 bpm, 180 bpm, 200 bpm, 220 bpm, 240 bpm, 260 bpm, 280 bpm, and finally to 300 bpm. The participants attempted to match this cadence progression in each condition. Participants engaged in both conditions and researchers used random assignment to determine the participants’ order of conditions (AB or BA). All participants were given a 10 second preparatory trial prior to each condition to help familiarize the participants to the movement patterns.

Statistical Analysis

Point relative phase was used as the primary dependent measure in order to examine the degree of interlimb coupling between the two upper extremities at either the shoulder or wrist joints. Relative phase, is defined as the relation between the phase angles of 2 separate oscillators (Rice and Newell, 2004).

The point relative phase is calculated using the formula:

Relative phase = 360º {(TLPD – TRPD)/TPL}

where TLPD is the time of the left limb peak displacement, TRPD is the time of the right limb peak displacement and TPL is the time period of the left limb oscillation (Yamanishim, Kauto, and Suzuki, 1979, 1980).

Therefore, the position of one oscillating upper extremity in relation to the other, simultaneously oscillating upper extremity will describe the degree of coupling between the two moving limbs. The relative phase was analyzed at both the shoulder and the wrist joints and then a comparison between the two conditions revealed which of the two oscillating joints was more coupled. In order to accomplish this, the researchers analyzed how far away the participants were from an out-of-phase or decoupled movement pattern. A decoupled movement pattern for the purposes of this study was a point relative phase of 0.5. A coupled movement pattern would be indicated by a point relative phase of 1.0. Therefore, the researchers calculated the participants' distance from 0.5 during the slow portion of each trial (i.e. the first forty seconds of the trial) and during the fast portion of each trial (i.e. the last forty seconds of each trial). The data were organized into four different groups. There were data for the shoulder during the slow cadence (shoulder/slow), shoulder during the fast cadence (shoulder/fast), wrist during the slow cadence (wrist/slow), and wrist during the fast cadence (wrist/fast). Then, a comparison of the difference between the shoulder and the wrist in regards to distance from 0.5 during the slow portion of the trials was made. Lastly, a comparison of the difference between the shoulder and wrist in regards to distance from 0.5 during the fast portion of the trials was made.

Gaps in the data of 10 samples or less were interpolated using 3rd order polynomial. Additionally the data were smoothed using a 10 Hz dual pass Butterworth filter. This filter is efficient at filtering out high frequencies and smoothing the data. A one-way analysis of variance (ANOVA) was utilized to analyze the differences between the mean difference from the decoupled movement pattern of 0.5 at the shoulders and the wrists. Therefore, the one-way ANOVA assessed whether or not there was a statistically significant difference in regards to how far individuals where away from 0.5 when oscillating at the shoulders in comparison to when oscillating at the wrists.

Results

The hypothesis that the proximal shoulder joint is more coupled than the distal wrist joint was supported by this study. The wrist joint was more capable of maintaining a decoupled movement pattern during the faster and the more difficult portion of the trials (Table 1).

During the slow portion of the trials, both joints were able to maintain a decoupled oscillatory movement pattern. According to Figure 1, the shoulder joints were capable of maintaining a decoupled movement pattern during the slow condition (*M*=0.0983, *SD*=0.0543) as were the wrist joints (*M*=0.0992, *SD*=0.0878). The means for the shoulder/slow and wrist/slow conditions were not statistically different from each other (Table 1). So, the results suggest that both joints performed similarly in terms of how far away they were from a decoupled relative phase of 0.5 during the slow cadences.

During the fast portion of the trials, there was a statistically significant difference between the shoulder and wrist joints in terms of decoupling as seen in Table 1. As seen in Figure 1, participants were significantly better at maintaining a decoupled movement pattern at the wrist (*M*=0.0647, *SD*=0.0605) than at the shoulder (*M*=0.104, *SD*=0.0885). The results indicate that the shoulder joints were farther away from a decoupled relative phase of 0.5 in comparison to the wrist joints. Interestingly, the wrist joints improved their distance from 0.5

during the fast portions of the trials. The wrist joints improved this distance from 0.0992 during the slow portions to 0.0647 during the fast portions. The possible explanations for this finding will be addressed in the discussion section.

Discussion

Data from this study indicate that the shoulder and wrist joints are capable of maintaining a decoupled movement pattern during a slow or easy task. During the slow portion of the condition, there was no statistically significant difference between the wrist and shoulder joints. However, when the task became more difficult, the participants were more capable of sustaining a decoupled movement pattern at the wrist joint than at the shoulder. Results indicated a statistically significant difference between the wrist and shoulder joints during the fast portion of the conditions suggesting that the wrist joint was less coupled than the shoulder joint. Furthermore, the wrist was more capable of maintaining a decoupled movement pattern during the more difficult, fast portion of the condition than during the easy portion. In other words, the performance of the wrist joint in terms of maintaining a decoupled movement pattern improved as the condition became more difficult.

The high degree of interlimb coupling found at the shoulder joint during the faster, more difficult portion of the trial supports the hypothesis that the shoulder would display a greater degree of interlimb coupling than the wrist. In concordance with the proposed hypothesis, the more proximal joint was limited to a more coupled movement pattern than the distal joint. The researchers hypothesized that the wrist would be more capable of engaging in a decoupled movement pattern due to the differences in amount of neuronal representation dedicated to the shoulder and wrist. When addressing the somatotopic arrangement and amount of representation dedicated to the different areas of the body, it is clearly apparent that the more distal portions of the upper extremity have more neuronal representation than the proximal portions (Lundy-Ekman, 2007). The areas that are more finely controlled (i.e. the wrists, hands, and fingers) are represented by larger portions of the somatosensory and primary motor cortex. The fine motor tasks that individuals engage in on a daily basis require higher degrees of dexterity and skill in comparison to the more gross motor movements such as those seen at the shoulder joint. Therefore, the amount of neuronal representation for these areas needs to be greater in order to successfully complete the fine motor movements.

The results of this study indicated that the wrist was more capable of maintaining a decoupled movement pattern than the shoulder. Relating this to statements in the previous paragraph, it can be understood that the faster cadences corresponded to a more difficult portion of the conditions. Therefore, as the difficulty of the trials increased and the cadences became faster, the wrist was better able to maintain a decoupled movement pattern due to the increased neuronal representation dedicated to the more distal parts of the upper extremity. The increased representation allows for the improved performance while engaging in two different tasks at the same time. Li et al. (2005) suggested that the distal joints (i.e. wrist) play a more superior role than the proximal joints (i.e. elbow and shoulder) in their effects on overall coordination during interlimb and intralimb movements. The results of this study suggest that the more distal portions of the upper extremity are in fact more capable of engaging in a decoupled movement pattern and thereby are different in terms of their movement capabilities when compared to the shoulder joints. As the conditions became more difficult, the wrist was not only more capable of attaining a decoupled movement pattern than the shoulder, but it actually improved when compared to slow cadences. In other words, as the trials became more difficult and the cadences increased in speed, the wrist improved in its ability to maintain a decoupled movement pattern.

The findings from this study are in concordance with several past research studies that indicate the influence of interlimb coupling on bilateral movement patterns (Kelso et al., 1979a; Kelso et al., 1979b; Marteniuk, MacKenzie, & Baba, 1984; Sherwood, 1994; Swinnen, 1991; Swinnen et al., 1992; Swinnen et al., 1998; Rogers et al., 1998). More specifically, this study demonstrates a statistically significant difference between the wrist and shoulder joints as the condition became more difficult. A study by Swinnen et al. (1992) showed that higher movement speeds resulted in a greater degree of interlimb coupling. They also found that attempting to produce movements with different spatiotemporal patterns became significantly more difficult at higher speeds. The results from Swinnen and colleagues' study are pertinent to an understanding of the current research study.

In regards to the current research study, data indicates that as the metronome increased in speed, the shoulder joint was less able to maintain a decoupled movement pattern. As the task increased in difficulty, the shoulder was less able to meet the demands of the task. Contrarily, the wrist was better able to maintain a decoupled pattern during the faster, more difficult portion of the condition. Therefore, opposite to previous research (Swinnen et al., 1992), the wrist improved in regards to decoupling as the task became more difficult. However, it is important to note that the requirements for this current research study were very different from those of Swinnen and colleagues' study. In this research project, the participants were entirely free to move their upper extremities in space thereby encompassing the x, y, and z axes. However, in the Swinnen and colleagues study, the participants' movements were limited to the horizontal plane because the apparatus that they used only allowed the flexion and extension movements to occur in that plane. Also, the coupling patterns identified in their research were limited to the elbow joints and did not indicate coupling from movements at the other joints.

Kelso (1984) found that increasing the frequency of alternating actions resulted in a higher degree of interlimb symmetry or coupling. Similarly, in this research study, the shoulder was drawn toward a coupled movement pattern as the number of oscillations required by the cadence increased. In other words, the results demonstrated that the faster the cadence, the higher the degree of interlimb coupling at the shoulder joint. However, also in this research study, increasing the frequency of oscillations at the wrist joint resulted in improved performance. As the cadence increased, the wrist joints were still able to participate in a decoupled movement pattern. Interestingly, the wrist joint was actually better able to match the demands of the cadence as it became faster. These results are not in concordance with Kelso (1984).

Another study examined whether or not there was an influence of spatial constraints in the coordination and control of the upper extremities during bimanual movements (Franz, Zelaznik, & McCabe, 1991). The subjects were instructed to draw a line with one limb and a circle with the other limb. During the other conditions, the participants created straight lines or circles using one arm at a time and then again using both arms (i.e. bimanual technique). Altogether, there were four single hand conditions (i.e. straight line with right arm, straight line with left arm, circle with right arm, and circle with left arm) and four dual hand conditions (i.e. dual straight lines, dual circles, straight line with left arm/circle with right arm, and straight line with right arm/circle with left arm). The results demonstrated that when participants were instructed to complete two movements of different spatial forms (i.e. circles and lines); they tended to exhibit spatial accommodation in the performances of both tasks. Spatial accommodation means that the limbs tried to complete the shape they were instructed to complete, but tended to complete a shape in between a circle and a line. This indicates that when the upper extremities are completing a bimanual task that has different spatial demands for each limb, the limbs tend to be drawn towards completing shapes that have similar spatial characteristics. Von Holst (1937/1973) termed this as the magnet effect.

The researchers state that the tendency was for the drawings to look very similar to each other by the end of the 20 second trial(s) despite the participants' attempts to complete two different drawings. In other words, circles, when performed concurrently with lines, became more line-like and lines looked more like circles. Referring back to von Holst (1937), the researchers suggest that there is a spatial magnet effect that is operating while the two limbs are attempting to complete two different patterns simultaneously. Furthermore, the results suggest that spatial constraints greatly affect the coordination of bimanual movements and impact overall control of the upper extremities (Franz et al., 1991). Combining the results from Kelso (1984) and Franz et al. (1991), research indicates that the upper extremities are coupled both spatially and temporally during bilateral movements.

Using relative phase and determining the distance from an out-of-phase movement pattern allowed the researchers in the current study to assess whether or not the participants were oscillating in a spatially coupled or decoupled movement pattern. The results indicate that the shoulder was especially drawn towards a spatially coupled movement pattern during the more difficult portion of the trial. This suggests that the shoulder is more spatially coupled than the wrist because the wrist was able to maintain a decoupled movement pattern better than the shoulder. A spatial magnet effect was seen often as one upper extremity would adapt the contralateral extremity's movement pattern especially in the shoulder during the fast portion of the trial. The study by Franz and colleagues and the current study both indicate an underlying neurological drive to perform spatially symmetrical movements. However, Franz et al. (1991)

did not study the difference between the different joints, so the current study's findings indicate that this neurological drive varies from the proximal joints to the distal joints.

Interestingly, in the current study, the wrist was not only better than the shoulder during the fast portions of the trials, but the wrist was more decoupled during the fast portion than during the slow portion. The results indicate that the wrist was more accurate at maintaining a decoupled movement pattern during the more difficult portions of the trials. Due to lesser requirements, it would be assumed that the wrist would be much more capable of moving in a decoupled fashion during the slow, easy portion of the trials, but this was not found. The shoulder was less capable of maintaining a decoupled movement pattern during the fast portion of the trials. It might be that during the slow portion, each upper extremity acted as a unit; that is, the shoulder and the wrist moved in synchrony to each other. In effect the two joints were 'locked' in terms of intralimb coupling. However, in the fast portion, the shoulder and the wrist became decoupled and were no longer locked together in synchrony. The wrists moved in a more decoupled fashion compared to the more coupled motion pattern of the shoulder joints.

Von Holst (1937/1973) described the tendency of a limb to try to oscillate at its own preferred frequency even while oscillating in a coupled frequency with the contralateral limb. This tendency was referred to the maintenance tendency. Rice and Newell (2004) suggest that individuals have a preferred rate of oscillation which their bodies will attempt to maintain even if there has been a cerebrovascular accident. The results of the current study could be analyzed from the viewpoint of a preferred rate of oscillation. As mentioned earlier, the wrist performed better during the fast portion of the trials as indicated by a mean difference score that was closer to a relative phase of 0.5 (out-of-phase). It could be possible that the slow portion of the trials consisted of a cadence that was slower than the preferred rate of oscillation for the wrist. Due to the increased cortical representation and the greater degree of use seen at the distal parts of the upper extremity, it is possible that the wrist joint would prefer a faster rate of oscillation. Therefore, as the cadence increased in speed, the rate of oscillations became easier to match for the wrists because they became more similar to their preferred rate.

Due to the results of this study, implications for researchers and occupational therapists have been identified. First and foremost, this study is effective in furthering the body of knowledge that exists concerning interlimb coupling. This study provides a more in-depth understanding of the concept of interlimb coupling and how it varies at different joint locations throughout the upper extremity. As with any concept, research must begin with a basic examination and analysis of its general parameters before more thorough research can be conducted. As will be discussed later, this study opens up new avenues of research that occupational therapists can explore in regards to interlimb coupling and everyday occupations. Therefore, the information that exists on the topic of interlimb coupling has been bolstered by the completion of this study.

Secondly, this study encourages the utilization of bilateral treatment strategies for individuals with upper extremity dysfunction that has been caused by a stroke or other disability. Based on the literature, it is apparent that the movements of one upper extremity impact the movements of the other upper extremity during bilateral movements (von Holst, 1937/1973; Dounskaia et al., 2010; Swinnen et al., 1992; Kelso et al.; 1979; Kelso, 1984; Peper and Beek, 1999; Rice and Newell, 2004). During bilateral movements, there exists an innate drive toward symmetry, especially at the more proximal joints in the upper extremity. These findings have been displayed in individuals with and without disabilities. Therefore, utilizing bilateral upper extremity treatment techniques may increase the activation of the damaged hemisphere through the activation of the undamaged hemisphere. Prior research has demonstrated that the affected upper extremity displays improvements in various aspects pertaining to movement when engaged in a bilateral task as opposed to a unilateral task (Harris-Love et al., 2005; Utley and Sugden, 1998; Li et al., 2005; Whitall et al., 2000; Luft et al., 2004; & Mudie and Matyas, 2000). Bilateral treatment techniques must be encouraged, but the therapist should be careful to ensure that the patient is not solely relying on the unaffected arm to complete tasks. Some tasks that would require the individual to incorporate bilateral movement patterns include cleaning a table with a cloth, painting with a roller while using both arms, kneading dough using a rolling pin, placing boxes or other items of various weights on shelves, and several other options exist. As always, the therapist must incorporate occupations that meet the patient's level of functioning and should attempt to find the just-right challenge for each patient.

The neural mechanisms that govern interlimb coupling are far from understood. It is believed that the ipsilateral projections of the supplementary motor area (SMA) and the primary motor cortex (PMC) impact bilateral movements (Lundy-Ekman, 2007; Martini, 2005; Schwerin, Dewald, Haztl, Jovanovich, Nickeas, & MacKinnon, 2008). If a stroke causes damage to the right hemisphere, then it will typically result in motor impairment to the left upper extremity. However, there is often an increase in the motor cortical activity of the hemisphere ipsilateral to the affected extremity (Schwerin et al., 2008). Additionally, ipsilateral motor evoked potentials (MEPs) have been shown to elicit more axial and proximal muscle activity than distal muscle activity (Bawa, Hamm, Dhillon, & Gross, 2004; Fujiwara, Sonoda, Okajima, & Chino, 2001). Researchers suggest that this finding is due to the ipsilateral projections innervating the more proximal muscles while the contralateral projections are responsible for the innervation and fractionation of the more distal muscles (Bawa et al., 2004; Fujiwara et al., 2001; Palmer &

Ashby, 1992; Schwerin et al., 2008). Therefore, the axial and proximal muscles are more likely to benefit from ipsilateral projections than distal muscles in the event of a head injury. In relation to this study, it is apparent that the more distal muscles are better able to engage in a more difficult and decoupled movement pattern. With respect to motor recovery, one needs to be aware of the differences in functional capabilities between the wrist and the shoulder and understand that proximal recovery may be more apparent due to the ipsilateral projections. Additionally, the distal muscles are reliant upon the cortical reorganization of the contralateral hemisphere, thereby requiring more time and rehabilitation for the motor recovery of these muscles (Schwerin et al., 2008).

Although the study is the first to directly analyze the difference between the wrist and shoulder joints in terms of interlimb coupling, there were limitations. First, the mean age of the participants was 24.38 years of age. The results of the study are thereby not generalizable to older adults. Similarly, only one participant was left-handed, so the results are mainly directed toward healthy, right-adults in their twenties or early thirties. One may argue that individuals who are left-handed may perform differently than those who are right-handed. Also, the results are not generalizable to individuals with disabilities because the sample population consisted of healthy adults.

In addition, a limitation of this study involves the participants' ability to match the increasing cadence. Some subjects tended to reach a comfortable rate of oscillation and then disregard the increasing cadence. In other words, they found a preferred rate of oscillations and refrained from speeding up their oscillations even when the cadence increased in speed. The researchers instructed the participants to increase their speed based on subjective observations of the participants' performance. However, there were not methods in place to ensure that the participants were oscillating at the same rate that the cadence was sounding other than verbal prompting. A method for calculating whether or not participants were accurately matching the pace of the cadence should be implemented.

Also, two minute trials were very demanding for many participants. Many noted fatigue in their upper extremities after completing one or both of the trials. In order to minimize the effects of fatigue, the trials could be shortened. In order to examine the same dependent variables that were investigated in this study, the increasing speed of the cadence would also have to be adjusted accordingly by requiring shorter periods of time at each cadence. Researchers' observations also indicated that participants tended to flex at the elbow joint as they became more fatigued. To ensure that participants were maintaining a static position, researchers should utilize a brace that holds the elbow in an extended position. A brace was not utilized in the current study due to the reflective marker that was positioned at the elbows. Future research should account for these markers by either utilizing less markers or by placing the marker on the brace.

The concept of interlimb coupling has been studied thoroughly throughout the years, but there are still opportunities available for furthering the understanding of interlimb coupling and its components. Future research should assess the degrees of interlimb coupling that occur during the completion of daily occupations such as cleaning a table or donning a shirt. Researchers should design a study that requires the participants to complete an asymmetric bilateral occupation that requires a degree of decoupling. They could then analyze the coupling seen throughout everyday occupations and discuss their impact on daily life. These research studies that assess coupling dynamics that drive upper extremity movements are important so that practitioners can become more aware of the underlying forces at work during bilateral movements.

To our knowledge, this study was the first to compare the degree of interlimb coupling at the shoulder and at the wrist during a bilateral oscillatory movement. Therefore, more research is needed to re-examine these finding and help solidify the results that suggest there is a difference between the shoulder and wrist joints in terms of interlimb coupling. Future studies should utilize both healthy populations and populations of individuals with disabilities. Involving individuals who are both typically developing and have a type of disability will help make the findings more generalizable to the entire population as a whole. In addition, using larger sample sizes with individuals of various ages will aid in the strength of these findings.

In conclusion, the results demonstrate that there was a statistically significant difference between the shoulder and wrist joints during the fast cadences throughout the study. More specifically, the wrist was more capable of maintaining an out-of-phase or decoupled movement pattern during the faster, more difficult part of the trials. These results suggest that the wrist was more successful at engaging in a decoupled movement pattern than the shoulder as the trial became more difficult. More research is needed in this area and should be extended to persons exhibiting hemiplegia, such as those with stroke, head injury, or cerebral palsy.

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Table 1:

Mean, standard deviation, F statistic, and significance values for the two conditions during the slow and fast cadences. The first significance (p value) corresponds to the difference between the shoulder and wrist joints during the slow portions of the trials. The second significance corresponds to the difference between the shoulder and wrist joints during the fast portions of the trials.

Conditions	**Mean difference in Relative Phase from 0.5**	**Standard Deviation**	***F***	***p***
Shoulder/Slow	0.0983	0.0543	0.002	**0.963**
Wrist/Slow	0.0992	0.08782		
Shoulder/Fast	0.1041	0.0885	5.395	**0.028**
Wrist/Fast	0.0647	0.0605		

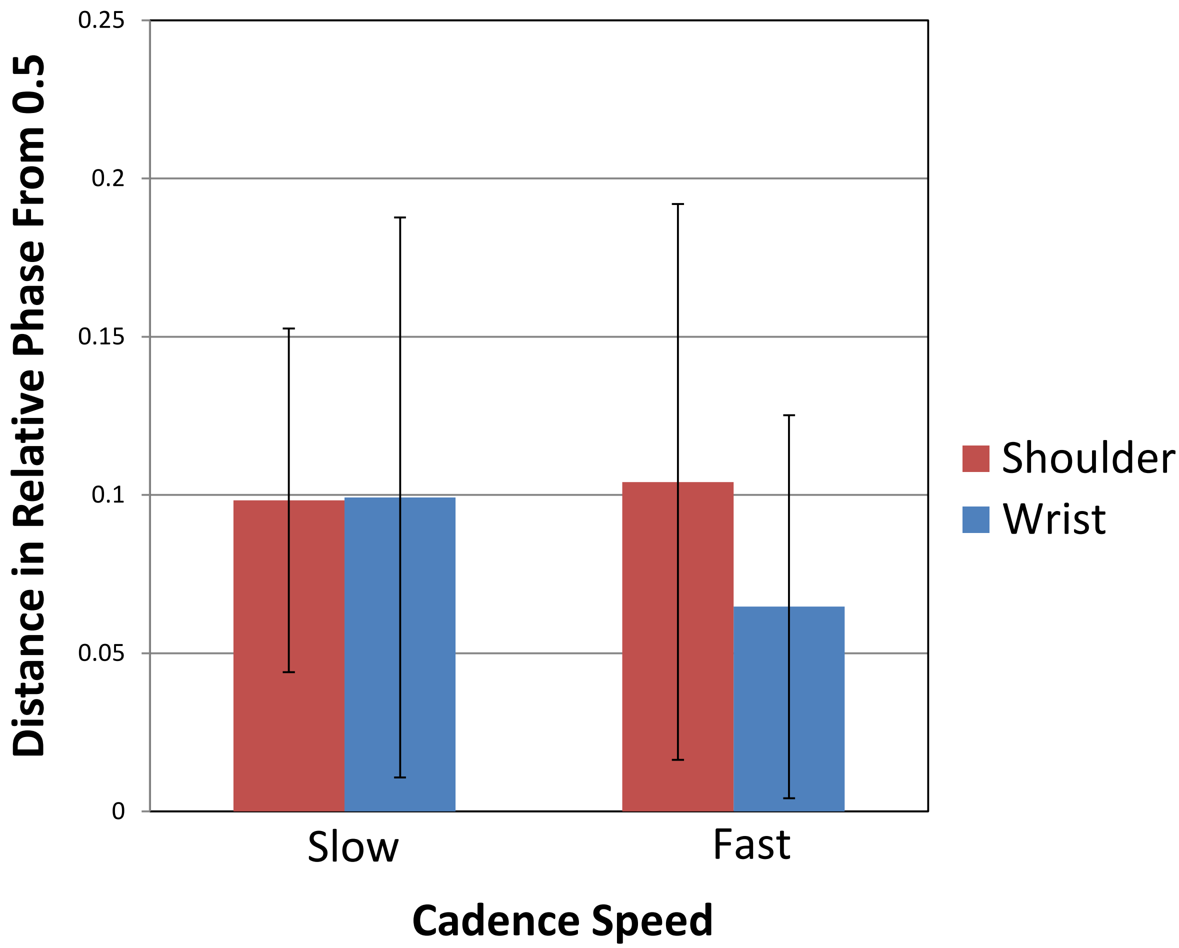

Figure 1: The participants' average distances in relative phase from a decoupled movement pattern of 0.5 across conditions while oscillating at slow or fast cadence speeds.

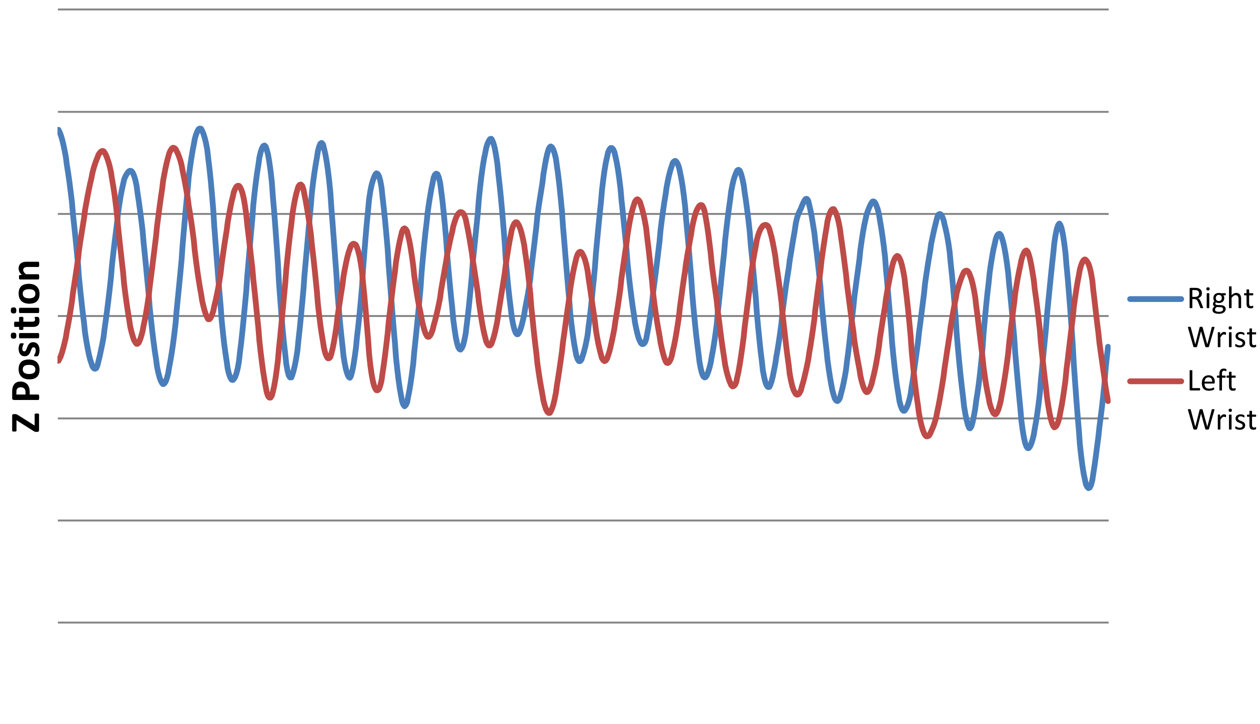

Figure 2: Example of a participant's stable decoupled movement pattern at the wrist joints.

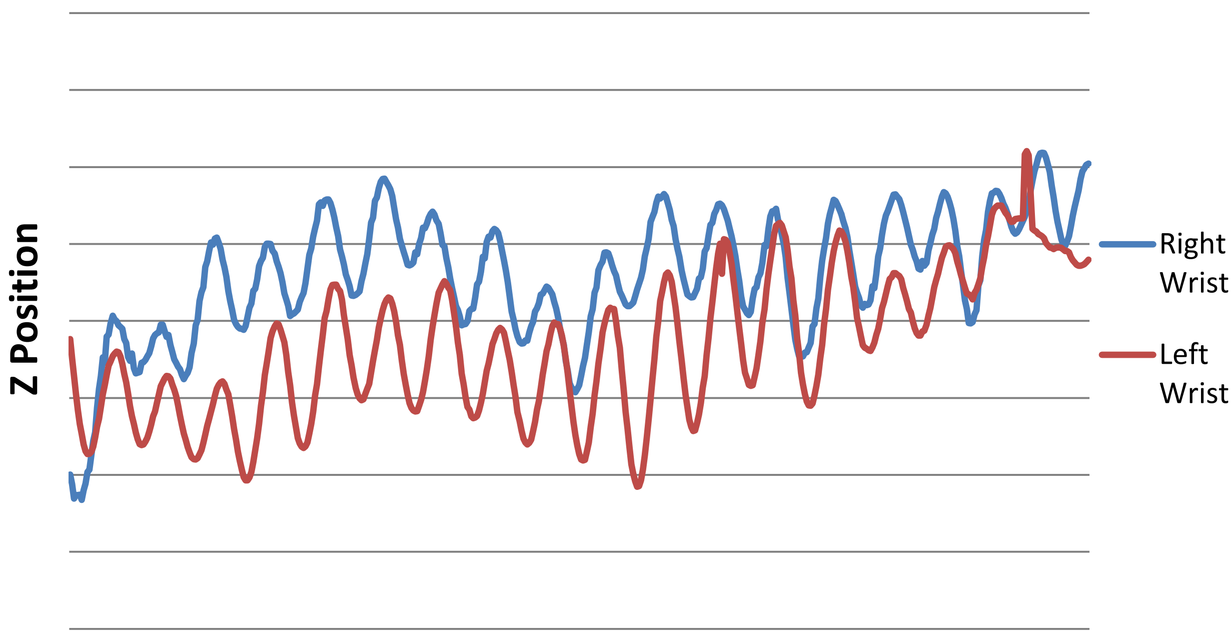

Figure 3: Example of a participant's coupled movement pattern at the wrist joints.