Postural and cognitive precursors of post-bout motion sickness and concussion-related symptoms in boxers

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Yi-Chou Chen

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Thomas A. Stoffregen

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Chapter 1 Introduction

Athletic Concussion

Concussion or mild traumatic brain injury (mTBI), is a type of traumatic brain injury (TBI), (CDC, 2014), which affects people of all cultures, genders, and ages worldwide. Concussion or mild traumatic brain injury occurs in a wide range of individuals including adults, adolescents, and children. As a result of its prevalence, concussion draws attention from educators, parents, coaches and administrators who are directly or indirectly involved in school physical education and sports programs. The incidence of athletic concussion is quite high, and the results can be serious and life altering. Data based on a large discharge survey from 1980 to 1995 showed that in the United States alone, each year concussions are associated with the death of 51,000 people, which approximately one-third of all injury death (Thurman & Guerrero, 1999, Thurman, Alverson, Dunn, Guerrero, & Sniezek. 1999). Furthermore, a concussion incident may be accompanied and followed with long lasting psychological problems. For example, A Swedish population study evaluated 218,300 TBI survivors and their 150,513 siblings (families comparison group), with about twenty two thousands control cases which were matched by sex and age from the general population (general comparison group). The data suggested that those who suffered from severe concussions had a three-fold increase in their odds of an earlier than normal mortality rate, even after confounding factors were adjusted, such as family history of psychological problems, or socio-economic status (Fazel, Wolf, Pillas, Lichtenstein, & Langstrom, 2014).

Some athletes sustain multiple concussions. Multiple concussions are related to long-term neuropsychological disorders, which may be present during or after athletic careers. For those who have multiple concussions there are potential risks associated with reduction in quality of life. For instance, Collins, Grindel, & Lovell, (1999) found that in 10 control groups, college football players who experienced two or more than two multiple concussions had poorer neuropsychological performance (Trail-Making Test and Symbol Digit Modalities Test), and a higher rate of learning disabilities (LD), than those in the control group. This study suggests that concussions can be independently connected to cognitive functions such as speed of information processing, and a long-term deficit in the domains executive functioning (e.g. ability to plan and execute a nonverbal behavior). Given the high rates of concussions and the potential for post-concussion consequences, it is critical to develop an early detection method for concussions or traumatic brain injury.

Definitions of Concussion

According to the first International Conference on Concussion in Sport, Vienna 2001 (Aubry, Cantu, & Dvorak, et al. 2002), Concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces. Several common features that incorporate clinical, pathological, and biomechanical injury constructs that may be used in defining the nature of a concussive head injury, include:

1. Concussion may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.

> 2. Concussion typically results in the rapid onset of short-lived impairment of neurologic function that resolves spontaneously.
>
> 3. Concussion may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury.
>
> 4. Concussion results in a graded set of clinical symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically follows a sequential course; however it is important to note that in a small percentage of cases however, post-concussive symptoms may be prolonged.
>
> 5. Concussion is typically associated with grossly normal structural neuroimaging studies (p. 6)

Based on these definitions, concussion refers to a wide range of head trauma. Symptoms can be defined from mild to severe based on other evaluation criteria. Yet concussion does not have a single, common sign. These widely different definitions suggest that there is a need for multiple evaluation methods from different scientific disciplines.

Concussion in Boxing

Boxing is an ancient sport that is practiced worldwide. Anecdotally, boxing is associated with the risk of head injury. In 1928, boxing was first associated with traumatic injury of the central nervous system in the form of dementia pugilistica syndrome, known as “punch drunk” (Martland, 1928).

> “Punch drunk most often affects fighters of the slugging type, who are usually poor boxers and who take considerable head punishment, seeking only to land a knockout

> blow. It is also common in second-rate fighters used for training purposes, who may be knocked down several times a day. Frequently it takes a fighter from one to two hours to recover from a severe blow to the head or jaw. In some cases consciousness may be lost for a considerable period of time" (Martland, 1928, p. 1103).

Although punch drunk is a chronic brain injury, which is not related to the evaluation of a concussion, a series of studies have examined boxing and brain injuries since Martland's research. Blonstein and Clarke (1957) took a retrospective method, and examined a seven-month period (October 1955 to April 1956) of boxing tournaments held by the London Amateur Boxing Association. Their examination looked at approximately 5,000 boxers. The study recruited boxers ranging in age from seventeen to twenty-six years old, who were judged as concussed during the boxing competitions, including those boxers who shown signs of concussion and were forced to rest for at least one month or longer by the ringside doctors. After the victims were recruited they were given a neurological examination and Electroencephalography (EEG). With this large sample size, Blonstein and Clarke assumed they could track all boxers who had been knocked out one or more times at the contests. The results showed, however, that during the season, only 29 boxers (0.58%) suffered from concussion related symptoms. Blonstein and Clarke believed that in each of the 100 contests, there was only one boxer who suffered from TBI (Blonstein & Clarke, 1957). However, the problem with this study is that all evaluations were basically relays on the decisions made by ringside doctors during the match. In recent years, there has been new evidence showing that evaluating concussions is difficult to measure. There are many unrecognized ringside concussive injuries in amateur boxers. Furthermore, loss of consciousness (LOC) is not the only indicator of examining a concussion (Moriarity, Pietrzak, Kutcher, Clausen, & McAward, 2012). LOC did not necessarily correlate with other indices of concussion severity, such as, the duration of symptoms (Erlanger, Kaushik, Cantu, Barth, Broshek, et al., 2003; Aubry, Cantu, Dvorak, Graf-Baumann, Johnston, et al., 2002, McCrea, Guskiewicz, Marshall, Barr, & Randolph, 2003). Therefore, the decisions from the ringside doctors could be underestimates. Given that LOC does not necessarily correlate with other indices of concussion, developing a comprehensive systematic approach to concussion would be of potential benefit to aid injured athletes and direct management decisions (Aubry, et al., 2002).

Since Martland’s (1928) work, boxing has become popular for studying concussion and other brain injuries. Studies of brain injuries in boxing are useful in several ways. These studies could plot a picture of all sport related brain injuries including concussion evaluations, postural control and concussion, biomarkers and long term neurodegenerative diseases through repeated concussions. Aside from tougher professional boxing matches, a fairly large number of studies have linked concussion, and cognitive decline to Olympic boxing (Loosemore, Knowles, &Whyte, 2007, Förstl, Haass, Hemmer, Meyer, & Halle, 2010, Enzenauer, Montrey, Enzenauer, & Mauldin, 1989). Yet Olympic boxing continues to be popularized, including the newly Olympic sport of female boxing.

Studies using both subjective and objective evaluations

Kaste, Kuurna, and Vilkki (1982), examined fourteen boxers (mean age of 31-years old) who had been Finnish, Scandinavian, or European boxing champions, who showed no evident signs of neurological problems. They found that of these fourteen boxers, only one boxer showed deficits in neurological status. However, when examined by a computed tomography (CT), pathological problems were revealed in four out of six professional, and one in eight amateur boxers, which could be attributable to brain injury. When EEG was used to examine all of the boxers, two of the professional boxers and four of the amateur boxers had electroencephalographic abnormalities, which may have been caused by brain injury. Twelve of the boxers had psychological test results, which suggested brain injury, although only two professional boxers showed a definite deviation from the norm. This study suggests that modern medical control of boxing cannot prevent chronic brain injuries, may also create a dangerous illusion of safety (Kaste, Kuurna, & Vilkki, 1982).

Other than underestimation by the ringside doctors, and under-detection by the medical devices, there was some aftermath of boxers that was revealed during autopsies. In these cases, brain abnormality was examined in much greater detail. The results from the autopsies clearly show the correlation between concussion and brain injury from boxing. Roberts, Allsop, & Bruton (1990) examined archival formalin-fixed sample from twenty boxers with dementia pugilistica, including five samples from amateur boxers and one sample from a boxer who died during the professional fight. They used silver, Congo red staining and an immunocytochemical method to obtain the extent of tangle and plaque formation of the brain tissues. Furthermore, the same brain sections of 20 confirmed Alzheimer’s cases and 20 age-matched-controls were examined in the same way as a comparison group. The results found, only by using the immunocytochemical method, but not silver and Congo red staining, that all dementia pugilistica cases with substantial tangle formation and evidence of extensive β-protein immunoreactive deposits (plaques) can be shown. The degree of β-protein deposition in boxers was comparable to those who have Alzheimer's disease. In addition, the molecular markers present in the plaques and tangles of DP are the same as those with Alzheimer's disease. Therefore, Roberts, et al., (1990) concluded that dementia pugilistica and Alzheimer's disease might share common pathogenic mechanisms leading to tangle and plaque formation (Roberts, Allsop, & Bruton, 1990).

Since Kaste, Kuurna, & Vilkki's (1982)'s work, many boxing and TBI related studies have been conducted. Different data has been presented, discussed and debated (Lampert & Hardman, 1984; Porter & O'Brien, 1996; Brooks, Kupshik, Wilson, Galbraith, & Ward, 1987; Loosemore, Knowles, & Whyte, 2007; Ross, Casson, Siegel, & Cole, 1987; Casson, Siegel, Sham, Campbell, &Tarlau, et al., 1984).

Today, the findings of Kaste, et al., (1982) seem valid. More evidence supports the hypothesis that boxing can cause brain injuries. Recently, new technology has been developed to examine head injury and neural inflammation. These technologies include ultrasensitive assay for CNS specific biomarkers, and a method to extract cerebrospinal fluid (CSF) (Zetterberg, Smith, & Blennow, 2013). The retrospective methodologies of evaluate concussion were valid and useful. For example, CSF is the body fluid that is in direct contact with the extracellular matrix in the brain. Therefore, the composition of CSF reflects biochemical changes after the brain was injured in any sport event. As a result it is considered a source of biomarkers of brain injury. Several CSF biomarkers of brain injury have already been established, including proteins that reflect Blood Brain Barrier (BBB), integrity and neuronal inflammation, axonal, neuronal, and astroglial damage. For instance, neurofilament light protein (NFL) is a biomarker of injury to large calibre myelinated axons. Total tau is a biomarker of injury to thin non-myelinated axons. Amyloid precursor protein (APP) and amyloid-β are produced in axon terminals and might be involved in synaptic activity and plasticity. Overproduction of amyloid-β in response to trauma could result in formation of diffuse amyloid plaques. On the other hand, injury to astroglial cells may lead to release of S100-B protein and glial fibrillary acidic protein (GFAP) into the extracellular matrix, which may increase S100-B levels in both cerebrospinal fluid and blood. Astrogliosis and post-injury neuroinflammation can result in increased production of interleukins and cytokines. Although no evidence shows this could connect to postural sway. It is clear, however, that the integrity of the blood–brain barrier is indicated by the cerebrospinal fluid: serum albumin ratio (Zetterberg, Smith, & Blennow, 2013). It would be valuable for the mechanisms of post boxing brain injuries to be revealed, even without the diagnostic confirmation of concussion. Evidence suggests that boxers who were not diagnosised of concussions after a bout did not necessarily mean that they didn't suffer from brain injuries.

For example, Neselius, Brisby, & Theodorsson et al., (2012) conducted a breakthrough examination of Olympic boxing matches and brain injury during actual boxing matches. In this study, several TBI related biomarkers were analyzed. These biomarkers include; NFL, GFAP, total tau (T-tau), and S-100B. Neselius, et al. (2012), used a prospective cohort approach, and examined 30 Olympic boxers and 25 non-boxing matched controls. Also, they used a lumber puncture method to collect biomarkers from Cerebrospinal fluid (CSF) through one-to-six days of boxing competition and after a period of fourteen rest days. The results shown that compared to the control group, after boxing, over 80% of

Olympic boxers showed significant concentrations of several TBI biomarkers, including NFL, GFAP, T-Tau and S-100. When compared to the control group, boxers' increased CSF levels of T-tau, NFL, GFAP, and S-100B demonstrated that there were minor central nervous injuries, and regularly trained Olympic boxers showed acute and cumulative effects from head trauma. Recurrent head trauma in boxing may be associated with increased risk of chronic traumatic brain injury. With more validated biomarkers and genetic tests neuronal damage caused by the blow(s) may be revealed (Kaste, et al., 1982; Jordan, Relkin, Ravdin, Jacobs, & Bennett, et al., 1997) so that there may be less dispute about the safety issues of boxing.

The extraction of CSF is not accessible, however, to many front line coaches or athletic trainers. Furthermore, given with the popularity of the sport, it is unlikely that boxing will cease, or further modification of rules will happen. Some researchers propose that boxing should be banned completely, but that is not a realistic solution to solve the problem of brain injury in boxing. Moreover, based on the statistics, boxing is not on the top list of sports that cause concussions, when compared to sports such as football and wrestling (Powell, & Barber-Foss, 1999; Kraus, & Conroy, 1984). In this case, a prospective method to detect potential concussive or sub-concussive individuals would be a better option.

Postural consequences of athletic concussion

The methods to evaluate sports related concussions have attracted much attention. One of the widely accepted methods of evaluation is the use of standing postural sway combined with specific visual tasks, such as reading. It has become an important research method over the years. Cavanaugh, et al., (2005, 2006) have demonstrated the value of standing body sway measures in the diagnosis of concussion, and in documenting recovery from concussion (Cavanaugh, et al., 2005 & Cavanaugh, et al., 2006). Standing body sway measures depend on the methodologies used in body sway and concussion evaluation. As a result, limited data is available that show a causal relation to the postural sway and concussion. Many factors cause postural sway, including internal factors such as heart rate and blood pressure. Postural sway itself is not always observable and meaningful, depending on what types of tasks are required of the individual. Measuring sway before head trauma may be a valuable indicator that can provide some clues for detecting susceptibility to concussion. In prior studies, Stoffregen, et al., (1991, 2000, 2012) have found that motion sickness and other strong indicators of concussion such as nausea, dizziness, and difficulty concentrating, can be prior detected through postural instability in laboratory experiments using optical stimulus. Furthermore, nausea and motion sickness are fairly common after a head injury (Beth Israel Deaconess Medical Center, 2013).

Studies using virtual reality (optical stimulus) and postural control on a force platform has been used in the assessment of concussion (Slobounov, Slobounov, & Newell, 2006). These studies indicated that there may be some common agreements on how to assess concussions, and thus the variables were widely accepted as part of the methodology. However, just like many other retrospective methods, the evaluations of concussions afterward seem limited in their value to prevent concussive events from the start. For example, the pathogenesis of a concussive event could be started from a postural control and cognitive disturbance rather than from actual physical impacts in the field. Based on this, if postural instability theory is sensitive enough to detect motion sickness and nauseogenic symptoms that are triggered by optic stimulus, it is logical to assume it could be used in a sports setting. Given that biological systems always deal with stronger stimulus, such as force impact or physical contact, postural instability theory may be effective for measurement.

At the same time, there are some prospective studies of concussion evaluation, which are effective at predicting the reoccurrence of the concussed rate in previously concussed individuals (Collins, Lovell, Iverson, Cantu, & Maroon, et al., 2002, McCrea, et al., 2003). The research clearly shows that individuals with prior concussion(s) are more vulnerable to additional concussions (Collins, Lovell, Iverson, Cantu, & Maroon et al., 2002; Harmon, Drezner, Gammons, Guskiewicz, & Halstead, et al., 2013; Guskiewicz, McCrea, Marshall, Cantu, & Randolph, et al., 2003). So far, however, very few investigations can predict whether individuals with no prior records of concussion will become concussed. In this dissertation, three studies were all focused on non-concussed athletes, because the symptom severity between “with history” or “without history” of concussion could be fatal. Therefore, it is important to evaluate the abnormal postural control of athletes prior to a sporting event and prevent the incidence of concussion before it happens.

Postural Instability and Motion Sickness

Riccio and Stoffregen (1991) developed a theory of motion sickness from the ecological approach to perception and action, which explains the control of orientation and self-motion. Riccio and Stoffregen argued that the change of stimulations of perceptual system is not the source that developed motion sickness. For example, some people misinterpret that motion sickness is the by-product, which yielded from the distinguished inconsistency between sensory (perception and action) systems. However, it cannot explain why people feel motion sickness symptoms after a heavy impact or multiple blows to the head (Chen, Hung, Tseng, Hsieh, & Chen, et al., 2012; Chen, Tseng, Hung, Hsieh, & Chen, et al., 2013). This trend does not seem linked to the inconsistency of different sensory inputs. On the other hand, there is no strong evidence showing that sensory inconsistency can be precisely measured (Stoffregen, and Riccio, 1991). Based on the postural instability theory of motion sickness, the symptoms proceed by the unstable control of the posture. Riccio and Stoffregen argued that the etiology of motion sickness was due to the instability of postural control of individuals, because they have not learned a strategy to control the body and be able to handle the situation that caused instability. The theory was proposed in the context of motion sickness as classically defined (Stoffregen, Hettinger, Haas, Roe, & Smart, 2000; Riccio and Stoffregen, 1991), but could be extended to encompass similar symptoms that arise in other situations, such as mTBI (Stoffregen, 2011).

A series of laboratory controlled setting have been tested on postural instability and motion sickness. For example, college students were recruited to play different types of console video games including car racing: Froza Motor Sport 2 (Dong, Yoshida & Stoffregen, 2011); first person shooter: Call of Duty Modern Warfare 2, (Chen, Dong & Stoffregen, 2012); or first person shooter on the mobile tablet (iPad 2) (Stoffregen, Chen & Koslucher, 2014). In each situation, 36 college students were separated into two groups. One group was given a force feedback joystick (Xbox 360) that allowed them to fully take control of the virtual car (or avatar) during a virtual racing and a warfare virtual battle. All participants were told that if they felt motion sick during gaming, they could stop the protocol immediately. The results showed that most of participants lost their head stability (increased variability) before they could hold any longer. Most of the participants then claimed they were motion sick, and had to quit their ongoing game play. The studies conducted in our lab have provided clues to the fieldwork of studies in this dissertation. Would those concussed athletes who fell on the ground, got hit to the head, or hit another athlete by head, due to their poor postural control and visual performance?

Motion Sickness and Head Trauma

Several studies reveal that motion sickness not only occurs in vehicular motion, simulator training or video gaming, but motion sickness also appeared to be a good predictor of post head injury (Brown, Brown, & Beattie, 2000; Jan, Camfield, Gordon, & Camfield, 1997). In a fairly large sampled prospective study (n = 563), Brown et al., (2000), found that children aged birth to thirteen-years old who experienced minor head injuries showed different symptoms after minor head injuries including vomiting, and motion sickness. Based on the data discussed above, it seems that motion sickness is not a single independent symptom, but one of the complications of minor to severe head injuries. In a series of laboratory experiments, Dong et al., Chen et al., and Stoffregen et al. detected loss of postural stability before participants reported motion sickness (Dong, et al., 2011; Chen, et al., 2012; Stoffregen, et al., 2014). Stimulus from optic array in the lab controlled motion sickness protocols were relatively minor, but still capable of induced loss of postural stabilities and disorientation before people felt motion sick. Therefore it may be valuable to bring these controlled lab finding to the field, and test them in different national boxing competitions.

Hypothesis

In a series of studies I hypothesized that motion sickness and concussive symptoms can be predicted through differences in postural dynamics, including spatial and temporal sequence of postural sway before athletes actually stepped into the boxing ring. The rationale is that if people have postural or ocular control problems in preparation, such as during warm-up stage they could have more perception and action problems when they get into the boxing ring and actually box.

I tested the following hypotheses:

1). the post-bout motion sickness and concussive symptoms can be detected through pre-bout postural sway and visual tracking performance.

2). based on the nature of the human standing posture, the variability of postural sway can be adjusted by different stand width (e.g. 5 cm, 17 cm and 30 cm).

3). abnormal postural sway related to post bout concussive symptoms can be detected through time series analysis such as detrended fluctuation analysis (DFA).

Experiment 1: The study focused on national level adult boxing club competitions. The following assumptions were tested (1) Do boxers differ in postural variability before and after boxing (impacts to the head). (2) Do different stance widths (5 cm, 17 cm and 30 cm), influence the dynamic of postural control. Last, (3). Do postural dynamics influence visual letter tracking performances?

Experiment 2: From the developmental points of view, it is worth knowing whether pre-bout control problems exist in earlier aged adolescent boxers. The muscle-skeletal systems of adolescent groups are not fully developed, and they tend to not yet have full control of their torso. As a result: the following assumptions were tested (1) Do adolescent boxers (mostly young males) differ in postural control before and after boxing matches between those who reported motion sickness and those did not? (2) Due to their relatively smaller body size (mass) (to Experiment 1), do stance widths (5 cm, 17 cm and 30 cm), also influence the dynamic of postural control in adolescent boxers? (3) Will postural dynamics influence letter-tracking performances in these groups?

Experiment 3: In the last experiment, the study tested whether or not the abnormal pre-bout postural control and cognitive performances can be found in female adolescents? Anthropometric data shows that adolescent females might not develop as much muscle strength as those of males. The following assumptions were tested (1) Do adolescent female boxers differ in postural control before and after their boxing match between those reported motion sickness and those who do not? (2). A 25 to 30 minutes warm-up exercise, might enhance cognitive performance and increase postural sway (variability). (3) Compared to the control group and well groups, motion sickness in the group has a higher positional variability in pre-warm up and post warm-up.

The Content of this Dissertation

The results of these three experiments are presented in journal format. The first experiment is presented in Chapter 2, the second experiment is presented in Chapter 3 and the third experiment is presented in Chapter 4. Tables, figures are presented in each chapter (e.g. chapter 2, 3 and 4), whereas the references for all chapters are presented at the end of the dissertation.

Chapter 2

Pre-Bout Standing Body Sway Differs between Adult Boxers Who Do and Do Not Report Post-Bout Motion Sickness

Yi-Chou Chen[1], Ting-Hsuan Hung[2], Tzu-Chiang Tseng[3], City C. Hsieh[4], Fu-Chen Chen[5], Thomas A. Stoffregen[1]*

1. School of Kinesiology, University of Minnesota, Minneapolis, Minnesota, United States of America, 2.Office of Institutional Research, Edgewood College, Madison, Wisconsin, United States of America, 3. Graduate Institute of Sport Coaching Science, Chinese Cultural University, Taipei, Taiwan, 4. College of Well Being, Yuan-Pei University, Hsin-Chu, Taiwan, 5. Department of Recreation Sport and Health Promotion, National Ping-Tung University of Science and Technology, Ping-Tung, Taiwan

Correspondence:

Thomas A. Stoffregen

E-mail: tas@umn.edu

Pre-Bout Standing Body Sway Differs between Adult Boxers Who Do and Do Not Report Post-Bout Motion Sickness

Abstract

Background: Motion sickness is characterized by subjective symptoms that include dizziness and nausea. Studies have shown that subjective symptoms of motion sickness are preceded by differences in standing body sway between those who experience the symptoms and those who are not. Boxers often report dizziness and nausea immediately after bouts. We predicted that pre-bout standing body sway would differ between boxers who experienced post-bout motion sickness and those who did not.

Methodology/Principal Findings: We collected data on standing body sway before bouts. During measurement of body sway participants performed two visual tasks. In addition, we varied stance width (the distance between the heels). Postural testing was conducted separately before and after participants' regular warm-up routines. After bouts, we collected self-reports of motion sickness incidence and symptoms. Results revealed that standing body sway was greater after warm-up than before warm-up, and that wider stance width was associated with reduced sway. Eight of 15 amateur boxers reported motion sickness after a bout. Two statistically significant interactions revealed that standing body sway before bouts differed between participants who reported post-bout motion sickness and those who did not. Conclusions/Significance: The results suggest that susceptibility to motion sickness in boxers may be manifested in characteristic patterns of body sway. It may be possible to use pre-bout data on postural sway to predict susceptibility to post-bout motion sickness.

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Introduction

Boxing is characterized by high intensity cardiovascular activity, by intense concentration and, in many cases, by blows to the head. After bouts, boxers often experience headache, confusion, memory difficulties, fatigue, attention and concentration difficulties, and sleep disturbances that can persist for hours, days, weeks, or months (Ohhashi, Tani, Murakami, Kamio, and Abe, et al., (2002). Immediately after bouts, boxers often experience dizziness and nausea (Erlanger, Kaushik, Cantu, Barth, and Broshek et. al., 2003). These latter symptoms classically are associated with motion sickness and, indeed, boxers often refer to their acute post-bout symptoms as motion sickness. In the present study, our focus was on relations between motion sickness and standing body sway in adult boxers.

Postural sway and motion sickness

People often experience motion sickness when exposed to simulation and virtual environment systems. Examples include video games (Chang, Pan, Tseng, and Stoffregen, 2012; Dong, Yoshida, and Stoffregen, 2011), video projection systems (Akiduki , Nishiike, Watanabe, Matsuoka, and Kubo et. al., 2005, Villard, Flanagan, Albanese, and Stoffregen, 2008), head-mounted displays (Draper, Viirre Gawron, and Furness, 2001, Merhi, Faugloire, Flanagan, and Stoffregen, 2007) and flight simulators (Kennedy, Berbaum, and Lilienthal, 1997, Kennedy, Fowlkes, and Lilienthal, 1993, Stoffregen, Hettinger, Haas, Roe, and Smart, 2000) . Exposure to simulators and virtual environments is associated with generalized increases in postural sway (Akiduki, et. al., 2005; Kennedy, Berbaum, and Lilienthal, 1997; Kennedy, Fowlkes and, Lilienthal, 1993; Kennedy, and Stanney, 1996). That is, postural sway measured after using one of these systems differs from sway measured before exposure to the system. Typically, it is assumed that both motion sickness and postural sway effects are caused by the fact of being exposed to a virtual environment. However, several studies have revealed differences in postural activity between participants who (later) reported motion sickness and those who did not. Differences have been observed in the spatial magnitude of postural sway (Stoffregen, et al., 2000, Stoffregen, and Smart, 1998), with greater movement magnitude among participants who later reported motion sickness. Differences have also been observed in the temporal dynamics of postural sway, with greater temporal structure or self-similarity among participants who later reported motion sickness (Stoffregen, Yoshida, Villard, Scibora, and Bardy, 2010). These effects are not limited to virtual environments. (Nachum, Shupak, Letichevsky, Ben-David, and Tal, et. al., 2004) measured participants' standing sway before and after a sea voyage and related these data to the incidence of mal de debarquement (motion sickness that occurs after returning to land from a ship). Prior to a sea voyage, postural activity differed between sailors who reported mal de debarquement after sailing and those who did not. These effects provide the empirical motivation for the present study. Motion sickness-like symptoms, such as nausea and dizziness, characterize many conditions that typically are not considered to be related to motion sickness, such as altitude sickness (Singh, Khanna, Srivastava, Lal, and Roy et. al., 1969), vertigo (Lempert, and Neuhausser, 2009, Troost, 2004), and morning sickness in pregnancy (Gadsby, Barnie-Adshead, and Jagger, 1993), as well as boxing. Stoffregen, (2011) argued that there might be differences in postural sway between persons who are susceptible to these maladies and persons who are not susceptible. The documented relation between postural sway and the subsequent experience of visually induced motion sickness suggests that data on body sway might be used to predict susceptibility to motion sickness in individuals (Stoffregen, 2011). In the present study our primary aim was to test the hypothesis that postural sway before a bout would differ between boxers who experienced post-bout motion sickness and those who did not.

Modulating factors

Under controlled manipulations of stance width (the distance between the heels) body sway tends to be greater when the feet are close together, and less when the feet are farther apart (Day, Steiger, Thompson, and Marsen, 1993, Stoffregen, Villard, Chen, and Yu, 2011). Variations in stance width can also alter the temporal dynamics of sway (Yu, Yank, Katsumata, Villard, and Kennedy et al., 2010, Yu, Chung, Hemingway, and Stoffregen, 2012). When asked to stand comfortably, healthy adults typically place their heels about 17 cm apart (McCray, and Maki, 1997). However, selfselected stance width can change according to circumstances. During pregnancy women tend to select wider stance, that is, they increase the distance between the feet (Jang, Hsiao, and Hsiao-Wecksler, 2008). We also vary stance width rapidly in different situations. For example, mariners adopt wider stance width at sea than they do on land (Stoffregen, Chen, Yu, and Villard, 2009), and baseball players typically adopt a wide stance when batting. Of greater relevance to the present study, boxers typically adopt a wide stance in the ring. This habitual, task-specific choice may influence relations between stance width and standing body sway. An important additional factor is the experimental finding that wider stance reduces susceptibility to visually induced motion sickness (Stoffregen, et al., 2010). In light of these factors we elected to manipulate stance width, and we predicted that wider stance would lead to reduced sway in boxers. In the general population, standing body sway is influenced by variations in visual and cognitive tasks such as auditory reaction time, or visual task difficulty (Woollacott, Shumway-Cook, 2002). For example, sway magnitude is often reduced during performance of demanding tasks, such as reading, relative to sway during less demanding tasks, such as looking at a blank target (Yu, et al., 2010, Chang; Wade, Stoffregen, Hsu, and Pan, 2010; Stoffregen, Pagulayan, Bardy, and Hettinger, 2000; Prado, Stoffregen, and Duarte, 2007). Studies of standing body sway in athletes have evaluated eyes open and eyes closed conditions but have not included variations in visual tasks (Cavanaugh, Guskiewicz, Giuliani, Marshall, and Mercer et al., 2005; Cavanaugh, Guskiewicz, Giuliani, Marshall, and Mercer et al., 2006; Slobounov, Cao, Sebastianelli, Slobounov, and Newell, 2008; Gao, Hu, Buckley, White K, and Hass, 2011). We hypothesized that the magnitude and self-similarity of postural sway would be reduced during performance of a demanding visual task in boxers when tested before a bout.

The present study

In the present study, our primary objective was to determine whether standing body sway measured before a bout would differ between boxers who reported post-bout motion sickness and those who did not. We measured standing body sway before boxers entered the ring. After boxers completed their bout, we evaluated subjective symptoms that typically are associated with motion sickness. We predicted that patterns of pre-bout postural sway would differ between boxers who later experienced motion sickness and those that did not. We measured body sway in the absence of any external source of motion (i.e., there was no mechanical perturbation, such as occurs in moving platform posturography (Cavanaugh, et al., 2005; Cavanaugh, et al., 2006). In addition, unlike many previous studies we did not ask participants to stand ‘‘as still as possible’’ (Gao, Buckley, White, and Hass, 2011; Mackey, Rabinovitch, 2005); rather, we instructed participants to stand comfortably.

Methods

Ethics statement

The research protocol was approved in advance by the Yuan-Pei University IRB. Prior to data collection, we obtained informed consent from each participant. Testing was conducted at the Contender Fitness Boxing Club, New Taipei City, Taiwan during a national boxing competition for club level boxers. In Taiwan, club level refers to amateur boxers whose age and training background are compatible with rules of the World Series of Boxing of the International Boxing Association (known as AIBA).

Participants

Seventeen boxers participated. Due to time pressure relating to the schedule of bouts, two participants were not able to participate in postural testing and, for this reason, were deleted from our analyses. Accordingly, our sample included 15 individuals. All were male. They varied in age from 18–34 years (mean = 25.6 years, SD = 5.1 years), in height from 160–186 cm (mean = 173.5 cm, SD = 7.9 cm), and in weight from 53 – 106 kg (mean = 72.8 kg, SD = 15.7 kg).

Apparatus

Data on postural activity were collected using a force plate (AccuswayPlus, AMTI). We collected data on the kinematics of the center of pressure, sampled at 60 Hz in the AP and ML axes.

Procedure

We evaluated motion sickness incidence and symptoms using the Simulator Sickness Questionnaire, or SSQ (Kennedy, Lane, Berbaum, and Lilienthal, 1993). We used a modified version of the SSQ. The modification consisted of the addition of one question: Are you motion sick? In responding to this question, participants were required to circle either yes or no. For this study the SSQ was translated into Chinese. Data were collected in relation to each individual's first bout in the national competition. All data were collected on the day of the bout. Prior to their bout, boxers went through a warm-up routine, usually consisting of 5 minutes of light jogging, extensive stretching, and ‘‘mitten drills’’ in which they practiced different types of punches. The total duration of the warm-up was approximately 30 minutes. The warm-up increased heart rate and respiration and for this reason might influence postural sway which, in turn, might influence relations between pre-bout sway and post-bout subjective symptoms. To account for this possibility we measured postural sway before warm-up and again after warm-up. Before each participant went through his regular warm-up routine he completed the informed consent procedure, the first SSQ and the first session of postural testing. After completing the warm-up each participant completed the second SSQ and the second session of postural testing. Postural testing consisted of 6 trials, each 60 s in duration, standing on the force plate. We used a 2 (Inspection vs. Search) x 3 (Stance Width = 5 cm vs. 17 cm vs. 30 cm) design with one trial per session (before vs. after warm-up) in each of six conditions for a total of 12 trials per participant. Within each session the order of conditions was counterbalanced across participants. Visual targets used during postural testing were identical to those used by Stoffregen et al., (2000), and consisted of sheets of white paper 13.5 cm × 17 cm mounted on rigid cardboard. In the Search task the target was one of four blocks of English text, each consisting of 13 or 14 lines of text printed in a 12-point sans serif font. Before each trial the participant was given a target letter (A, R, N, or S) and asked to count the number of times the target letter appeared in the block of text. At the end of each trial, the participant reported the number of letters counted. The Search task resembled the King-Devick test, which has been used to assess cognitive consequences of head trauma in boxers (Galetta, Barrett, Allen, Madda, and Delicata et al., 2011). In the Inspection task, the target consisted of a blank sheet of white paper; participants were instructed to keep their gaze within the borders of the target. The Inspection task was similar to ‘‘quiet stance’’ conditions used in previous studies (Woollacott, Shumway-Cook, 2002) and can be considered a control condition for the Search task. Bouts consisted of three rounds (3 minutes per round), and could be terminated early in the event of knockout (KO) or technical knockout (TKO). The third SSQ was administered during the ‘‘cool down’’ period, 10 to 20 minutes after the bout.

Analysis of Postural Data

We separately evaluated the magnitude and temporal dynamics of postural activity. Magnitude measures, such as positional variability, velocity, and range, provide information about the size or spatial extent of movement (e.g., ‘‘by how many centimeters do COP data points tend to differ from each other?’’). Magnitude measures, by their nature, tend to eliminate or discard the temporal structure of movement data, that is, how the measured quantity varies in time (e.g., ‘‘to what extent does COP displacement at time A resemble displacement at time B?’’). Analyses that preserve information about the temporal structure of data on human movement (that is, analyses of the temporal dynamics of movement) are increasingly common (Kinsella–Shaw, Harrison, Colon–Semenza, and Turvey, 2006; Lin, Seol, Nussbaum, and Madigan, 2008), and can reveal changes in the temporal structure of postural activity in response to variations in visual tasks (Chen and Stoffregen, 2012). We assessed movement dynamics using detrended fluctuation analysis, or DFA. DFA describes the relation between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured (Chen, Ivanov, Hu, and Stanley, 2002). DFA has been used in several studies of the control of stance (Slobounov, et al., 2008), and in our own research on visually induced motion sickness (Dong, Yoshida, and Stoffregen, 2011; Villard et al., 2008; Stoffregen, et al., 2010). We did not integrate the time series before performing DFA. We conducted inferential tests on α, the scaling exponent of DFA, as derived from the COP data. The scaling exponent is an index of long-range autocorrelation in the data, that is, the extent to which the data are self-similar over different time-scales. Postural sway in healthy adults tends to be non-stationary, typically yielding $1.0 > \alpha > 1.5$ (Lin, Seol, Nussbaum, and Madigan, 2008). We conducted 2 × 2 × 2 × 3 repeated measures ANOVAs on factors Group (Sick vs. Well), Task (Inspection vs. Search), Warm up (Before warm-up vs. After warm-up), and Stance Width (5 cm vs. 17 cm vs. 30 cm). The dependent variables were the positional variability of the center of pressure, and α of DFA. Separate analyses were conducted for postural activity in the AP and ML axes. To accommodate any violations of the ANOVA sphericity assumption, we used the Greenhouse-Giesser correction (Winer, 1971), which adjusts the number of degrees of freedom used for individual comparisons in the ANOVA in response to violations of sphericity. Where appropriate we report the fractional degrees of freedom that characterize this correction. For statistically significant effects we used the partial η_2 statistic as a measure of effect size.

Results

Participants (and their coaches) indicated that they regularly trained and sparred at their local boxing clubs and participated in local, club level competitions. None of the participants had competed in any boxing tournament in the previous month. In the two weeks preceding the national competition all competitors had reduced schedules of sparring. This less intensive level of practice was maintained until the day of the competition. Thus, none of the participants had experienced a concussion or loss of consciousness during the two weeks prior to their participation in our study. None of the participants were diagnosed with a concussion following their participation in the study.

Visual performance

There was no measure of performance for the Inspection task. Following previous studies, we took for granted that participants maintained their gaze within the boundaries of the blank target (Stoffregen, et al., 2000). For the Search task, the dependent variable was the number of target letters that S reported at the end of each trial. We conducted a 2 × 2 × 3 repeated measures ANOVA on factors Group (Sick vs. Well), Time (Before warm-up vs. After warm-up), and Stance Width (5 cm vs. 17 cm vs. 30 cm). Visual performance was influenced by stance width, $F(2, 26) = 3.64$, $p = .04$. As shown in Figure 1, the number of letters counted was positively associated with greater stance width. There were no other significant effects.

Subjective symptoms

Before and after warm-up, each participant stated that they were not motion sick. After their bout, 8 participants stated that they were not motion sick. Seven of 15 (47%) stated that they were motion sick (should sum. Data on wins and losses are presented in Table 1.

Table 1. Bout outcomes for boxers in the Well and Sick groups.

	Total	Unanimous	Split	TKO-1	TKO-2	TKO-3
Well wins	6	3	1	1	0	1
Well loses	2	2	0	0	0	0
Sick wins	3	0	1	0	1	1
Sick losses	4	2	0	0	1	1

Bouts were evaluated by three judges. Unanimous: All three judges concurred on the winner. Split: Two judges agreed on the winner. Some bouts ended with a technical knockout, or TKO. In these bouts no judges' decision was needed. TKO-1, 2, 3 indicated the TKOs that occurred in the first, second, or third round. Doi:10.1371/journal.pone.0046136.t001

Data on symptom severity are summarized in Figure 2. In evaluating the severity of symptoms we used the Total Severity Score, which we computed in the recommended manner (Kennedy, et al., 1993). The third SSQ was completed approximately 15 minutes after each participant's bout. Before warm-up, SSQ scores did not differ between participants who later reported motion sickness and participants who did not, U = 31, p = .340. After warm-up, SSQ scores did not differ between participants who later reported motion sickness and participants who did not, U = 30, p =.386. After their bouts, SSQ scores were higher among participants in the Sick group than in the Well group, U = 42, p = .05.

Postural activity

For positional variability in the ML axis we found a significant main effect of Warm-up, F (1, 13) = 51.87, p =.001, partial η_2 = 0.800. Positional variability after warm-up (mean = 0.323, SD = 0.019) was greater than before warm-up (mean = 0.223, SD = 0.023). The main effect of Stance Width was also significant, F (1.22, 26) = 22.98, p = .001, partial η_2 = 0.639 (Figure 3a). Post hoc tests revealed that each stance width differed from each of the other two stance widths, each p =.008. There was a significant Group × Warm-up interaction, F (1, 6) = 14.94, p = .002, partial η_2 = 0.535 (Figure 4). Post-hoc comparisons revealed that, after warm-up, positional variability was greater for the Sick group than for the Well group, p =.001. Finally, the Warm-up × Stance Width interaction was significant, F (1.55, 20.13) = 7.42, p =.006, partial η_2 = 0.363 (Figure 5). Post-hoc comparisons revealed that stance width had a significant influence on sway after warm-up but not before warm-up, p =.05, confirming our prediction. For positional variability in the AP axis we found no significant main effects. There was a significant interaction between Group and Task, F (1, 13) = 6.69, p = .023, partial η_2 = 0.340, which is illustrated in Figure 6. Post-hoc tests revealed that for boxers in the Sick group sway was reduced during the Search task, relative to sway during the Inspection task, p =.05, whereas for boxers in the Well group sway did not differ as a function of visual task. In addition, there was a significant 3-way interaction between Task, Warm-up, and Stance Width, F (1.75, 22.69) = 4.69, p = .023, partial η = 0.265, which is illustrated in Figure 7. Post-hoc tests revealed that before the warm-up (Figure 7A) positional variability was reduced during performance of the Search task (relative to sway during performance of the Inspection task) when stance width was 17 cm, p = .018. For α of DFA in the ML axis we found a significant main effect of stance width, F (1, 1.351) = 77.13, p =.001, partial

η_2 = .847 (Figure 3b). Post-hoc tests revealed that each condition differed from both of the others. The effect of stance width on a in the ML axis resembled that reported by Stoffregen et al. (2010), their figure 7 for healthy undergraduates (mean age = 20 years). For α of DFA in the AP axis there were no significant effects.

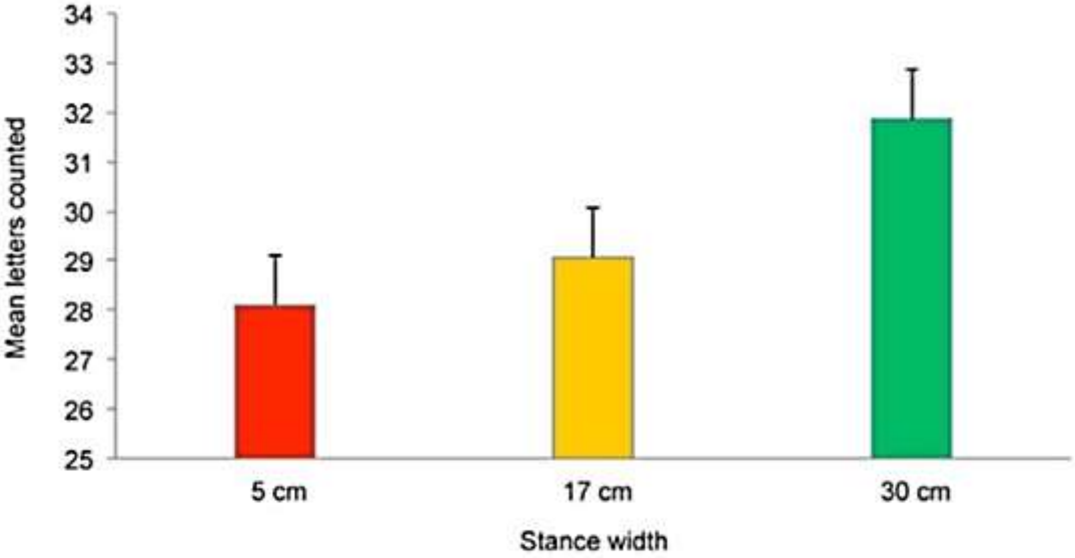

Figure 1. Performance on the Search task (mean letters counted per trial) as a function of stance width. The error bars represent standard error of the mean.
doi:10.1371/journal.pone.0046136.g001

Discussion

Using a simple, non-invasive testing protocol, we measured the standing body sway of amateur boxers before they entered the ring for a competitive bout. After completing the bout boxers reported the presence and severity of motion sickness. Measures of standing body sway taken before the bout differed significantly between boxers who did and did not report motion sickness after the bout as a function of time (before warm-up versus after warm-up) and as a function of visual task (Inspection vs. Search). The present study appears to be the first to document relationships between pre-bout postural sway and post-bout motion sickness.

Boxers relative to the general population

Postural sway often is reduced during performance of difficult visual tasks, relative to sway during performance of easy visual tasks (Woollacott, and Shumway-Cook, 2002; Stoffregen, 2000). In previous studies body sway has been measured in the absence of any physical exertion and with participants adopting their preferred stance width. In the present study we found the same effect under comparable conditions (i.e., before warm-up, with stance width = 17 cm; Figure 7A). In the general population, the positional variability of postural sway is inversely related to stance width (Day, et al., 1993) (Day, et al., 1993; Stoffregen, et al., 2011). In the present study we found the same effect in the body's ML axis (Figure 3). In these two ways the body sway of boxers in the present study resembled effects documented in the general population. While stance width influenced postural sway, it also influenced performance on the visual search task: Wider stance was associated with increases in the reported count of target letters (Figure 1). Yu et al., (2010) observed a similar effect in the context of visual performance among mariners on a ship at sea.

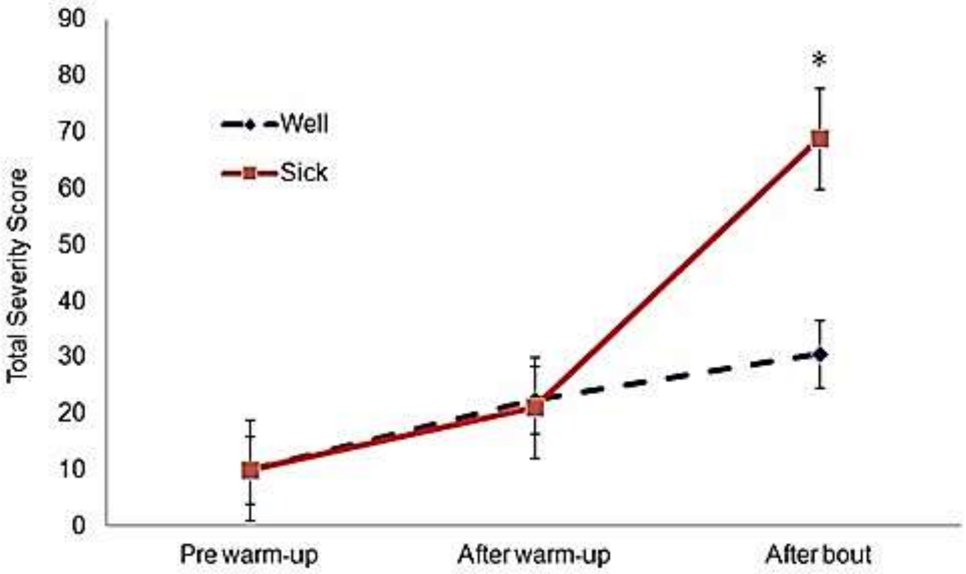

Figure 2. Severity of motion sickness symptoms as measured using the Total Severity Score of the Simulator Sickness Questionnaire. *, post-hoc difference between Well and Sick groups after completion of bouts, p < .05. The error bars represent standard error of the mean. doi:10.1371/journal.pone.0046136.g002

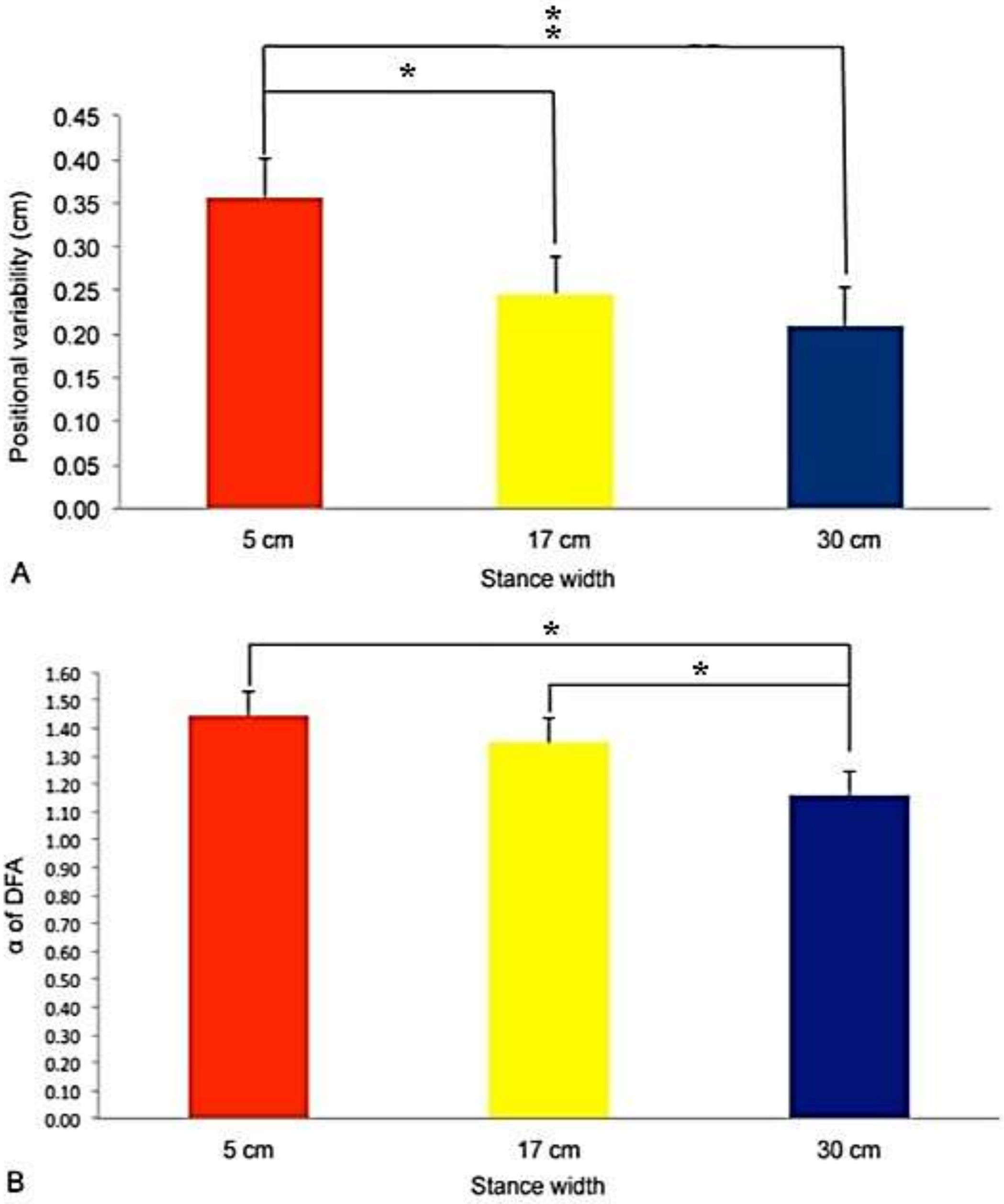

Figure 3. Postural activity in the ML axis as a function of stance width. A. Positional variability of the COP. B. Self-similarity of COP positions as quantified by a, the scaling exponent of detrended fluctuation analysis. *, p < .05; ** p < .01. The error bars represent standard error of the mean. doi:10.1371/journal.pone.0046136.g003

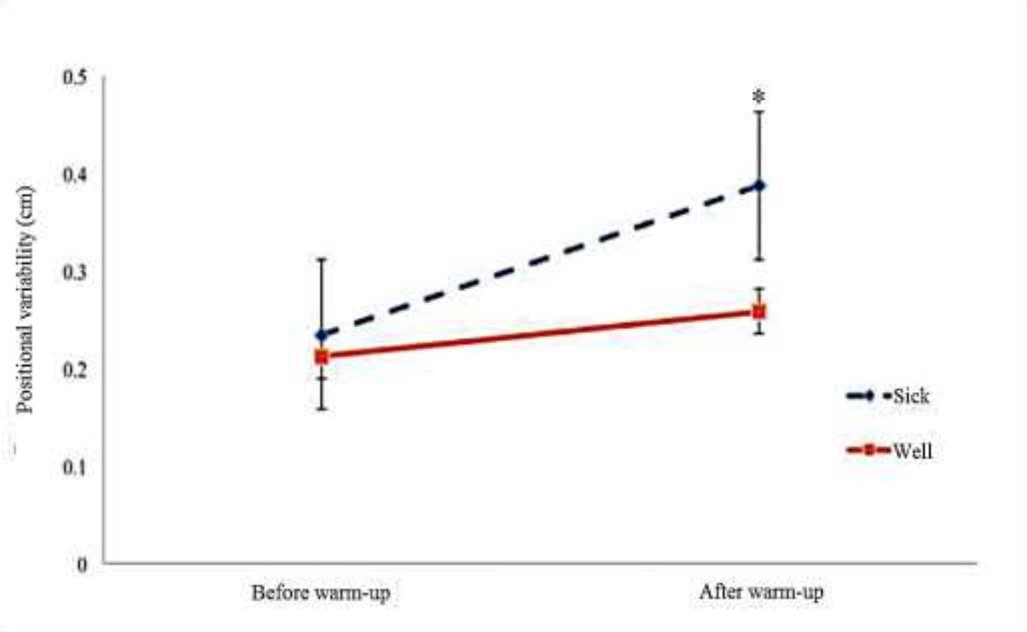

Figure 4. Positional variability of the COP in the ML axis before and after warm-up for the Well and Sick groups. *, post-hoc difference between Well and Sick groups after boxers completed their warm-up routine, p < .05. The error bars represent standard error of the mean. doi:10.1371/journal.pone.0046136.g004

Postural effects of pre-bout warm-up routine

Body sway differed before and after the pre-bout warm-up routine. As expected, the positional variability of the COP was greater after warm-up than before warm-up, but this was true only for sway in the ML axis. Warm-up also increased the influence of stance width on the positional variability of the COP in the ML axis (Figure 5).

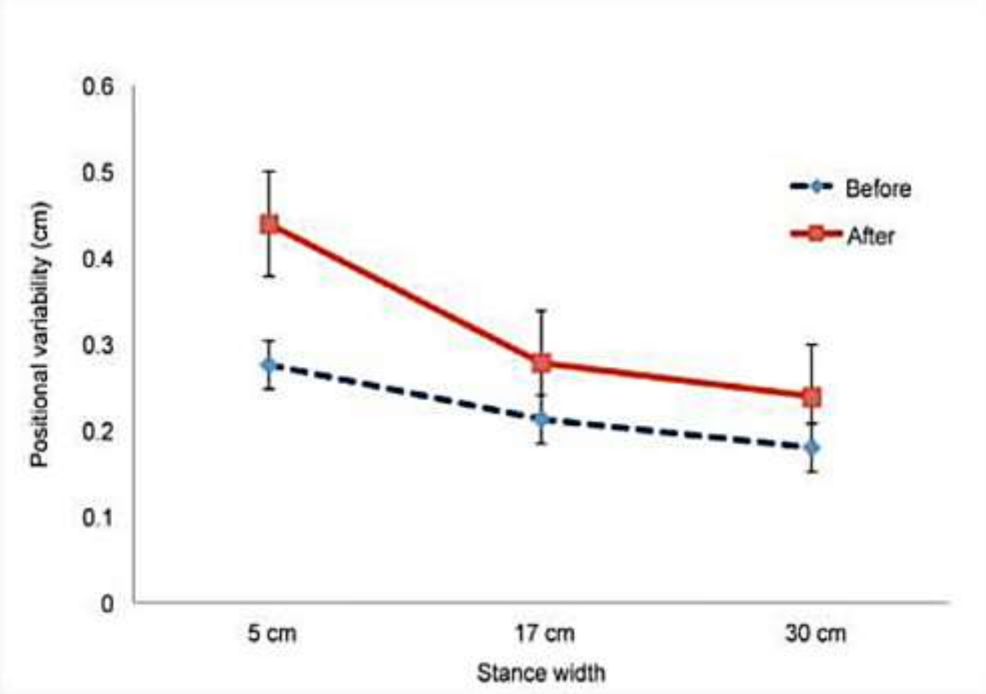

Figure 5. Positional variability of the COP in the ML axis before and after warm-up as a function of stance width. The error bars represent standard error of the mean. doi:10.1371/journal.pone.0046136.g005

These effects can be explained by the increased physiological arousal that occurs during warm-up. By contrast, in the AP axis positional variability did not exhibit an overall increase following warm-up; rather, the effects of warm-up were modulated by stance width and visual task (Figure 7). Warm-up influenced the positional variability of sway but had no effect on the temporal dynamics of sway; that is, warm-up increased the magnitude of sway not its temporal structure.

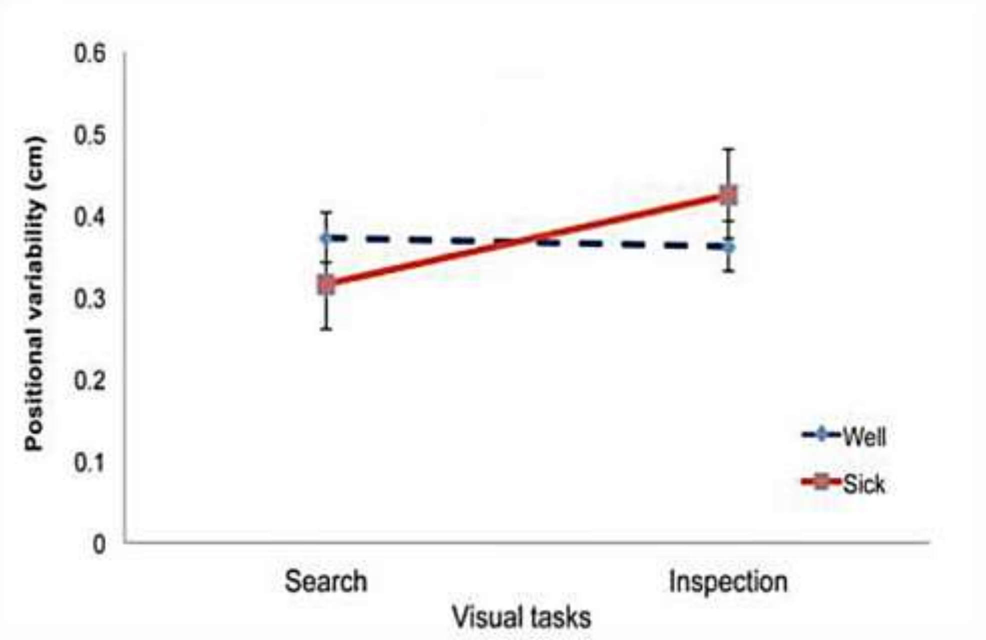

Figure 6. Positional variability of the COP in the AP axis during performance of the Inspection and Search tasks for the Well and Sick groups. *, post-hoc effect for the Sick group, sway was reduced during performance of the Search task, relative to sway during performance of the Inspection task, p< .05. The error bars represent standard error of the mean. doi:10.1371/journal.pone.0046136.g006

Pre-bout postural sway and post-bout motion sickness

Our principal hypothesis was that postural sway before a bout would differ between boxers who reported motion sickness after the bout those who did not. This prediction was confirmed for the positional variability of the COP. In previous research on the general population of healthy adults we have examined relations between visual motion, postural sway, and motion sickness (Stoffregen, et al., 2000; Stoffregen, et al., 2000). In those studies, we found that changes in postural sway occurred among individuals who reported visual motion sickness, and that these changes began before the onset of subjective symptoms of visual motion sickness. In the present study we found similar effects: Postural sway differed between boxers who did and did not report motion sickness, and these changes existed before boxers entered the ring. After warm-up, the positional variability of the COP in the ML axis was greater for boxers who reported post-bout motion sickness than for boxers who did not (Figure 4). One possible interpretation of this effect is that participants in the Sick group were less able than their Well peers to compensate for postural effects of physiological arousal. An alternative interpretation is that, after warm-up, participants in the Sick group relaxed their criterion for ‘‘comfortable’’ stance. We also found that our manipulation of visual tasks influenced the positional variability of the COP in the AP axis for Sick boxers, but not for Well boxers (Figure 6). Participants in the Sick group tended to reduce their sway during performance of the Search task, relative to sway during performance of the Inspection task. Modulation of postural sway in response to different visual tasks has been reported in many studies (Woollacott and Shumway-Cook, 2002; Stoffregen, Hove, Bardy, Riley, and Bonnet, 2007). Separately, the control of standing body sway can be affected by clinical conditions such as aging (Prado, et al., 2007) and Parkinson’s disease (Schmit, Riley, Dalvi, Sahay, and Shear et al., 2006). Clinical conditions can also influence the task specific modulation of standing body sway. For example, children with autism spectrum disorder modulate their sway in response to variations in visual tasks (Chang, et al., 2010), but children at risk for developmental coordination disorder do not (Chen, Stoffregen, and Wade, 2011). The present study provides the first evidence that task specific variation in postural sway may be related to individual differences in susceptibility to motion sickness.

Causal factors

Dizziness, nausea and vomiting are common acute symptoms of concussion (Erlanger, et al., 2003; McCrea, Guskiewicz, Marshall, Barr, and Randolph, et al., 2003). In addition to these subjective symptoms concussion also is associated with changes in standing body sway, both in the immediate aftermath of head trauma (Erlanger, et al., 2003) and up to several months later (Cavanaugh, et al., 2005; Cavanaugh, et al., 2006; Slobounov, et al., 2008; Peterson, et al., 2003). Boxing is widely associated with concussion (Galetta, et al., 2011; Moriarity, Pietrzak, Kutcher, Clausen, and McAward, et al., 2012). Given the results of the present study these facts suggest that pre-bout postural sway may be related to an individual's susceptibility to concussion. In future research it will be important to examine possible relations between pre-bout postural sway, post-bout motion sickness, and concussion. It may be possible to use pre-bout data on postural sway as a predictor of susceptibility to boxing-related concussion. We were not able to record the number or severity of blows to the head during bouts. It is possible that participants in the Sick group sustained more blows to the head, or more severe blows to the head, than participants in the Well group. Such a relation would be expected if post-bout motion sickness were causally related to head trauma (either concussive or sub-concussive) experienced during individual bouts. We predict that pre-bout postural sway would differ between boxers who did and did not experience post-bout motion sickness when controlling for the number and severity of blows to the head experienced by each boxer. Similarly, a person's experience of post-bout motion sickness might vary from bout to bout, that is, a person who did not experience motion sickness after one bout might experience it after a subsequent bout, and vice versa (as one example, if participants who did not experience motion sickness in the present study were paired to fight each other, then they might experience motion sickness in this second bout). In particular, known long term effects of concussion on body sway (Peterson, Ferrara, Mrazik, Piland, and

Elliott, 2003, Cavanaugh, et al., 2006; Slobounov, et al., 2008; Peterson, et al., 2003) indicate lingering effects of concussion on motor control which, in turn, might increase susceptibility to motion sickness-like symptoms in subsequent bouts. It would be interesting to conduct a longitudinal study evaluating pre-bout postural sway and post-bout motion sickness in the same individuals over a succession of bouts. Such a study would make it possible to determine whether relations between pre-bout postural sway and post-bout motion sickness persist across bouts.

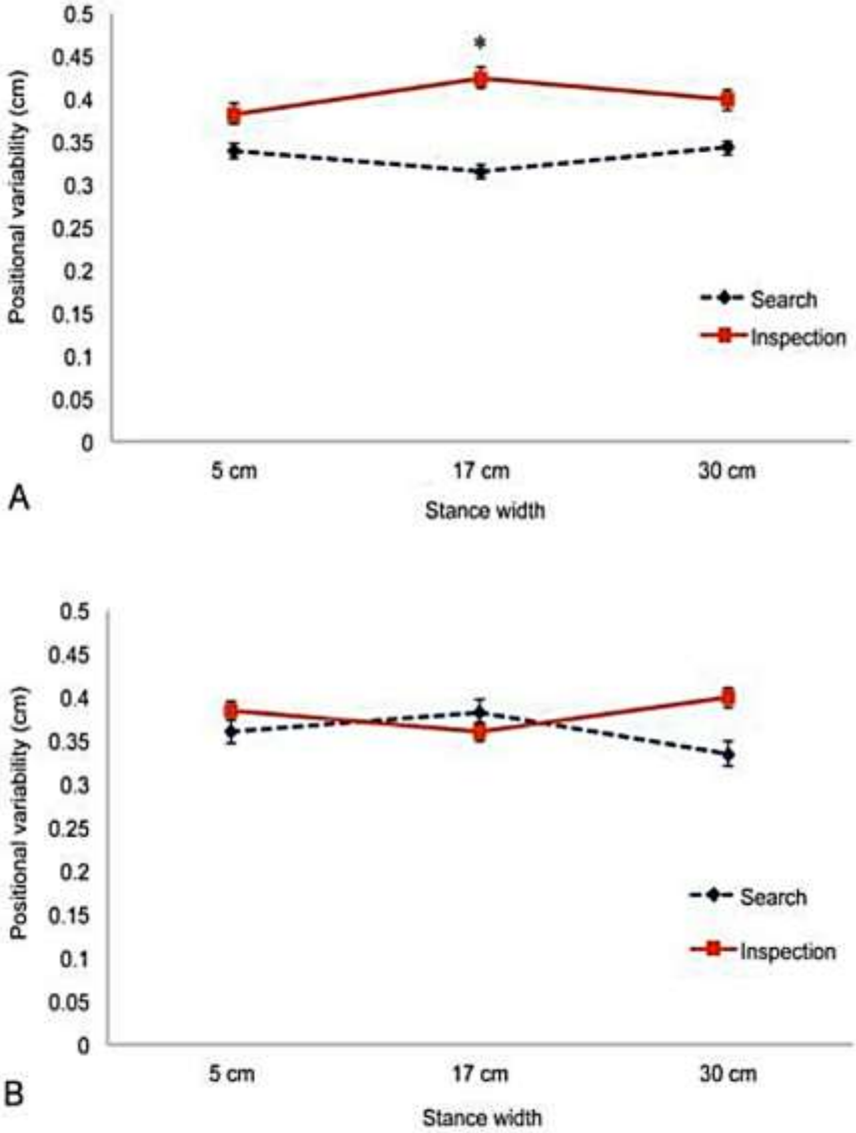

Figure 7. Positional variability of the COP in the AP axis as a function of stance width during performance of the Inspection and Search tasks. A. Before warm-up. B. After warm-up. *, post-hoc effect showing that before warm-up sway was reduced during performance of the Search task, relative to sway during performance of the Inspection task, when stance width was 17 cm, p,.05. The error bars represent standard error of the mean.
doi:10.1371/journal.pone.0046136.g007

It is important to recall, however, that in the present study none of the participants were diagnosed with a concussion following their participation. Motion sickness is a common consequence of athletic concussion (Erlanger, et al., 2003; McCrea et al., 2003); however, athletes sometimes experience motion sickness in the absence of concussion, and in the absence of any head trauma (Kondo, Nakae, Mitsui, Kagaya, and Matsutani, et al., 2001; Kraemer, Noble, Clark, and Culver, 1987). Thus, in the present study it is possible that post-bout motion sickness occurred in the absence of significant head trauma. The preceding possibilities are not mutually exclusive; that is, it may be that post-bout motion sickness has multiple causal factors, including but not limited to head trauma sustained during the bout. This is an area for future research.

Conclusion

We conducted the first assessment of the quantitative kinematics of standing body sway in boxers. We used data on pre-bout postural sway in a prospective manner. We showed that before entering the ring there were differences in standing body sway between boxers who experienced post-bout motion sickness and those who did not. These effects suggest the possibility that objective, non-invasive measures of postural control might be helpful in evaluating susceptibility to boxing-related concussion.

Author Contributions

Conceived and designed the experiments: Y-CC TAS CCH. Performed the experiments: T-HH T-CT. Analyzed the data: Y-CC F-CC TAS. Wrote the paper: TAS Y-CC F-CC.

Chapter 3

Cognitive and Postural Precursors of Motion Sickness in Adolescent Boxers

Yi-Chou Chen[1], Tzu-Chiang Tseng[2], Ting-Hsuan Hung[3], City C. Hsieh[4], Fu-Chen Chen[5], & Thomas A. Stoffregen[1]*

1 School of Kinesiology, University of Minnesota, United States of America

2 Graduate Institute of Sport Coaching Science, Chinese Cultural University, Taiwan

3 Office of Institutional Research, Edgewood College, United States of America

4 College of Well Being, Yuan-Pei University, Taiwan

5 Department of Recreation Sport & Health Promotion, National Pingtung University of Science and Technology, Taiwan

Correspondence:
Thomas A. Stoffregen
E-mail: tas@umn.edu

Cognitive and Postural Precursors of Motion Sickness in Adolescent Boxers

Abstract

Athletic head trauma (both concussive and sub-concussive) is common among adolescents. Concussion typically is followed by motion sickness-like symptoms, by changes in cognitive performance, and by changes in standing body sway. We asked whether pre-bout body sway would differ between adolescent boxers who experienced post-bout motion sickness and those who did not. In addition, we asked whether pre-bout cognitive performance would differ as a function of adolescent boxers' post-bout motion sickness. Nine of nineteen adolescent boxers reported motion sickness after a bout. Pre-bout measures of cognitive performance and body sway differed between boxers who reported post-bout motion sickness and those who did not. The results suggest that susceptibility to motion sickness-like symptoms in adolescent boxers may be manifested in characteristic patterns of body sway and cognitive performance. It may be possible to use pre-bout data to predict susceptibility to post-bout symptoms.

Introduction

Sports, such as soccer, American football, and boxing, are associated with head trauma, including concussive and sub-concussive impacts. Sport participation is most common among adolescents (i.e., post-purbertal children) and, in part for this reason concussion is more common among adolescents than other age groups (Loosemore, Knowles, and Whyte, 2007). Many studies have examined phenomena relating to head trauma in adults (Ohhashi, Tani, Murakami, Kamio, and Abe, et al., 2002), or in mixed adult and adolescent samples, typically in collegiate settings (Barr, & McCrea, 2001). Fewer studies have examined these issues specifically in adolescents (Browne, & Lam, 2006, Thomas, Collins, Saladino, Frank, and Raab, 2011). Athletic head trauma is associated with degraded cognitive performance (Thomas, et al., 2011; Moriarity, Pietrzak, Kutcher, Clausen, and McAward, 2012) and with changes in standing body sway (Cavanaugh, Guskiewicz, Giuliani, Marshall, and Mercer, et al., 2005). Athletic head trauma is also associated with dizziness and nausea (Ohhashi, et al., 2002; Erlanger, Kaushik, Cantu, Barth, and Broshek, 2003). Dizziness and nausea are associated with motion sickness, and boxers (as one example) often refer to post-bout symptoms as motion sickness (Kotz, 1998). In adult boxers, the experience of motion sickness that occurs after boxing has been related to pre bout measures of body sway (Chen, Hung, Tseng, and Hsieh, 2012, and Chen, et al., 2012). In the present study, we asked whether post-bout motion sickness might be related to pre-bout measures of both cognitive performance and body sway in adolescent boxers.

Our research relating body sway to head trauma was inspired, in part, by research relating body sway to visually induced motion sickness. Before exposure to nauseogenic visual motion stimuli body sway sometimes differs between participants who later (i.e., after exposure) report motion sickness and those who do not. Such effects have been observed in mixed adult-adolescent samples (Stoffregen, Yoshida, Villard, Scibora, and Bardy, 2010), and in 10-year-old children (Chang, Pan, Tseng, and Stoffregen, 2012). These effects are consistent with the postural instability theory of motion sickness, in which unstable control of body posture is claimed to be a necessary and sufficient precondition of motion sickness (Riccio, and Stoffregen, 1991). Stoffregen (2011) argued that similar effects might exist in relations between pre-exposure body sway and other sources of motion sickness-like symptoms, such as concussive and sub-concussive head trauma.

In children, young and elderly adults' body sway is modulated in relation to the demands of cognitive tasks, such as reading (Chen, Tsai, Stoffregen, and Wade, 2011; Stoffregen, Pagulayan, Bardy, and Hettinger, 2000; Woollacott, and Shumway-Cook, 2002). Body sway displaces the head and eyes, and these natural displacements can influence the performance of cognitive tasks that require precise stabilization of the head and eyes (Stoffregen, Hove, Bardy, Riley, and Bonnet, 2007). Links between postural activity and motion sickness, on the one hand, and between postural activity and cognitive performance, on the other, raise questions about possible relations between all three. Research documenting head trauma in adolescents has not included data on body sway, cognitive performance, or on relations between cognitive performance and post-traumatic subjective experiences, such as motion sickness (Browne, and Lam, 2006; Thomas, et al., 2011). Following previous studies, among adolescent boxers we predicted that pre-bout standing body sway would differ during performance of different cognitive tasks (Chen, et al., 2012; Chen, et al., 2011; Stoffregen, et al., 2000, and Woollacott, et al., 2002).

Separately, we predicted that pre-bout cognitive performance would differ between boxers who reported post-bout motion sickness and those who did not.

We assessed adolescent boxers before and after they participated in a regulation sparring bout. Before bouts, we measured cognitive performance and standing body sway. After bouts, we measured motion sickness incidence and symptom severity. In pre-bout postural testing we also varied stance width (the distance between the heels), which affects standing body sway (Day, Steiger, Thompson, and Marsden,1993) and susceptibility to motion sickness (Stoffregen, et al., 2010). The design, independent, and dependent variables were the same as in Chen et al., (2012), who used adult boxers as participants.

Methods

Testing was conducted at a national sparring event at the Bei-Ling High School, Taipei, Taiwan. Boxing was supervised by three referees and a ringside physician.

Participants

Nineteen boxers participated from high schools in Taiwan, with boxing experience from 2 to 6 years. Sixteen were male and three were female, with mean age 15.6 years (SD = 1.1 years), mean height of 164.7 cm (SD = 5.8 cm), and mean weight of 53.3 kg (SD = 7.8 kg). Each participant reported that they had never been diagnosed with a concussion.

Apparatus

Data on postural activity were collected using a force plate (AccuswayPlus, AMTI). We recorded the kinematics of the center of pressure (COP), sampled at 60 Hz in the AP and ML axes.

Procedure

Participants were tested ringside before and after their first sparring bout. We evaluated motion sickness symptoms using the Simulator Sickness Questionnaire, or SSQ (Kennedy, Lane, Berbaum, and Lilienthal, 1993). The SSQ is a standardized questionnaire that assesses the severity of 16 different symptoms (e.g., nausea, disorientation), which was translated into Chinese. We modified the SSQ by adding a forced choice, yes/no question about motion sickness incidence: Are you motion sick? Participants first completed the informed consent procedure, after which they completed the SSQ and the first session of cognitive/postural testing. Participants then went through a 30-minute warm-up routine comprising jogging, stretching, and practice punches, after which participants completed the second SSQ and the second session of cognitive/postural testing. Cognitive/postural testing consisted of 6 trials, each 60 s in duration, standing on the force plate. We used a 2 (Cognitive tasks: Inspection vs. Search) × 3 (Stance Width = 5 cm vs. 17 cm vs. 30 cm) design with one trial per session (before vs. after warm-up) in each of six conditions for a total of 12 trials per participant. The order of conditions was counterbalanced across participants. To control stance width, participants stood with their feet on marked lines on the force plate.

Targets for the cognitive tasks were sheets of white paper 13.5 cm × 17 cm mounted on rigid cardboard (Stoffregen, et al., 2000). In the Search task the target was one of four blocks of English text, each comprising 13 or 14 lines of text printed in a 12-point sans serif font. Prior to each trial the participant was given a target letter (A, R, N, or S) and asked to count the number of times the target letter appeared in the text. After each trial, participants reported the number of letters counted. In the Inspection task, the target was a blank sheet of white paper; participants were instructed to keep their gaze within the borders of the target. Sparring bouts consisted of 3 rounds, with a 1-minute break between rounds. The duration of each round was 3 minutes for males, and 2 minutes for females. Bouts could be terminated early by the referee. SSQ3 was administered within 20 minutes after bouts.

Analysis of Postural Data

We assessed movement magnitude in terms of positional variability, which we defined operationally as the standard deviation of COP position. We assessed the temporal dynamics of movement using detrended fluctuation analysis (DFA), which describes the relation between the magnitude of fluctuations in COP position and the time scale over which those fluctuations are measured (Chen, Ivanov, Hu, and Stanley, 2002). DFA has been used studies relating body sway to aging (Lin, Seol, Nussbaum, and Madigan, 2008) to cognitive performance (Koslucher, Wade, Nelson, Lim, and Chen et al., 2012), and to motion sickness (Stoffregen et al., 2010). We did not integrate the time series before performing DFA. We conducted inferential tests on α, the scaling exponent of DFA. The scaling exponent is an index of long-range autocorrelation in the data, that is, the extent to which COP positions are self-similar over different time-scales.

We conducted 2 × 2 × 2 × 3 repeated measures ANOVAs on factors Task (Inspection vs. Search), Warm-up (Before vs. After), Stance Width (5 cm vs. 17 cm vs. 30 cm) and Group (Sick vs. Well). Separate analyses were conducted for sway in the AP and ML axes. We used the Greenhouse-Geiser correction and, where relevant, we report the fractional degrees of freedom that this correction entails. We estimated effect size using the partial η_2 statistic.

Results

Subjective reports

Before and again after warm-up, each participant stated that they were not motion sick. After boxing, nine participants stated that they were motion sick (47.4%), and were assigned to the Sick group. Of these, 3 won their bouts and 7 lost. Ten participants stated that they were not motion sick and were assigned to the Well group. Of these, 6 won their bouts and 4 lost. Data on symptom severity are summarized in Figure 1. Before warm-up, SSQ scores did not differ between the Well and Sick groups, Mann-Whitney U = 48.5, p = .741 (two-tailed). After warm-up, SSQ scores were higher in the Sick group than in the Well group, U = 76, p = .009 (two-tailed). After boxing, SSQ scores were higher among participants in the Sick group than in the Well group, U = 73, p = .009 (one-tailed). Within groups, we used the Wilcoxon Signed Ranks test. For the Sick group, the mean after warm-up (SSQ2) was greater than before warm-up (SSQ1), z = 2.36, p = .005, and the mean after boxing (SSQ3) was greater than after warm-up (SSQ2), z = 1.73, p = .037. For the Well group, the mean after warm-up was greater than before warm-up, z = 2.02, p = .04, and the mean after boxing (SSQ3) was greater than after warm-up (SSQ2), z = 2.82, p = .005.

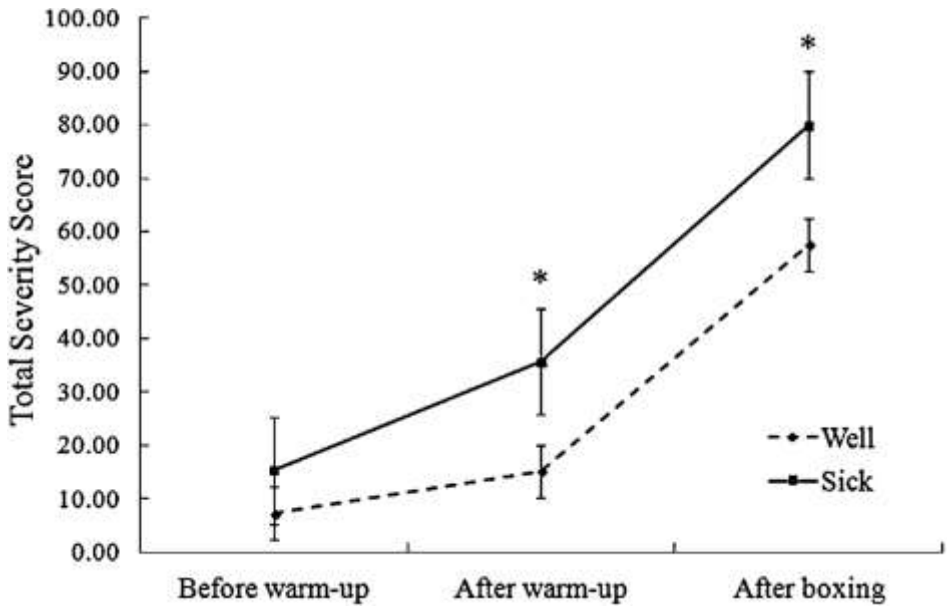

Fig. 1. Mean Total Severity Scores on the Simulator Sickness Questionnaire. The error bars illustrate standard error of the mean.

Cognitive performance

Following previous studies, in the Inspection task we took for granted that participants maintained their gaze within the boundaries of the blank target (Stoffregen et al., 2000). For the Search task, the dependent variable was the number of target letters reported. We conducted a 2 × 2 × 3 repeated measures ANOVA on factors Warm-up (Before warm-up vs. After warm-up), Stance Width (5 cm vs. 17 cm vs. 30 cm), and Group (Sick vs. Well). More letters were counted after the warm-up (mean = 27.43, SD = 1.18) than before warm-up (mean = 22.92, SD = 1.37), F (1, 17) = 15.56, p = .001, partial η_2 = .478, consistent with previous studies showing that cognitive performance can be enhanced by physical exercise (Lambourne, and Tomporowski, 2010). In addition, the Well group counted more letters than the Sick group, F (1, 17) = 5.92, p = 0.26, partial η_2 = 0.258 (Figure 2). There were no other significant effects.

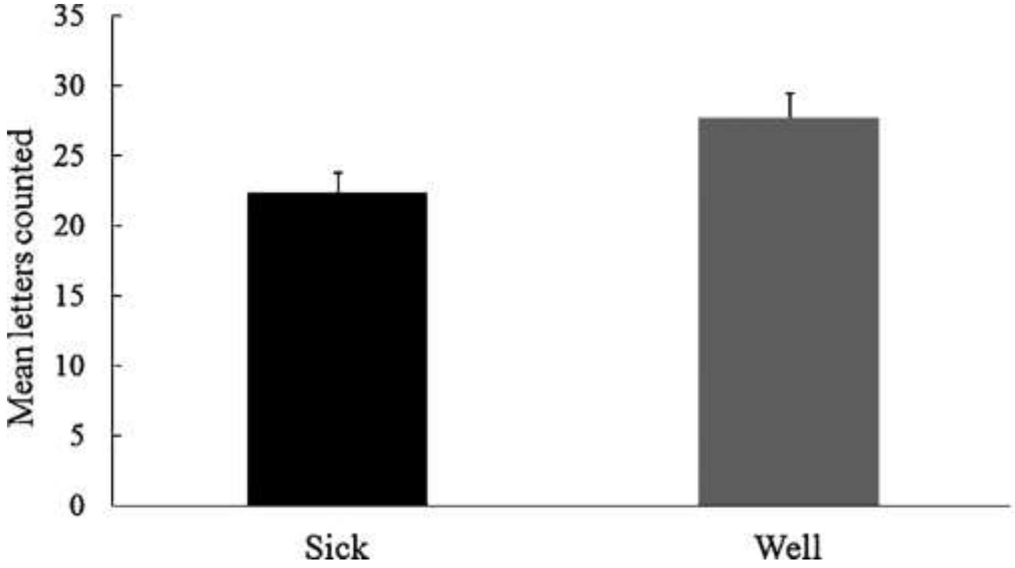

Fig. 2. Significant main effect of Group for performance of the search task. Error bars represent standard error of the mean.

Postural activity

For positional variability in the ML axis we found a significant main effect of Warm-Up, F (1, 17) = 7.50, p = .014, partial η_2 = 0.306. Positional variability was greater after warm-up (mean = 0.274, SD = 0.02) than before warm-up (mean = 0.233, SD = 0.01). The main effect of Stance Width was also significant, F (2, 36) = 17.87, p < .001, partial η_2 = 0.512, with narrow stance associated with greater positional variability (5 cm, mean = 0.318, SD = 0.02; 17 cm mean = 0.232, SD = 0.02; 30 cm mean = 0.211, SD = 0.03). There was Warm-Up × Stance Width interaction was also significant, F (1.8, 30.6) = 4.31, p = .026, partial η_2 = 0.202 (Figure 3).

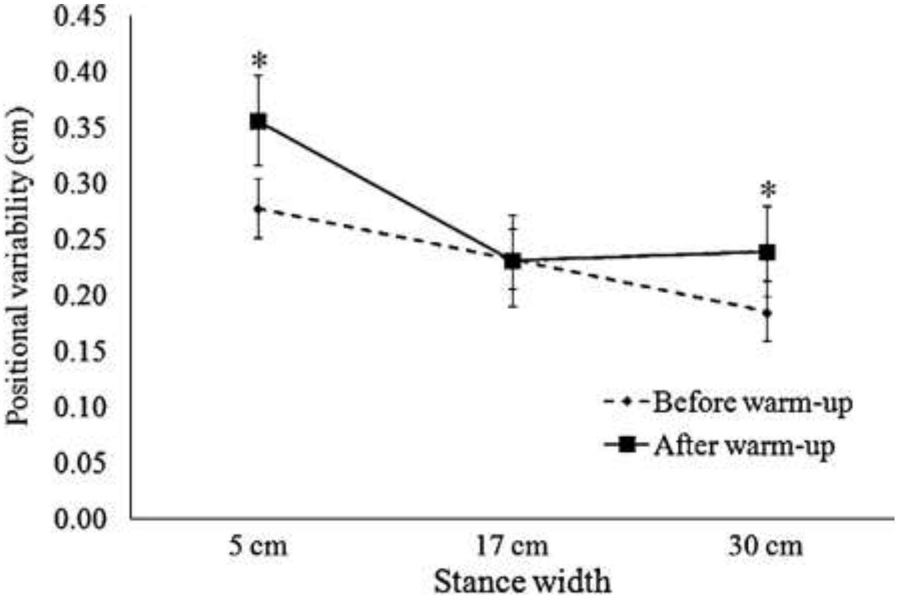

Fig. 3. Significant warm-up x stance width interaction for positional variability in the ML axis. Error bars illustrate standard error of the mean.

For the 5 cm and 30 cm stance width conditions, positional variability was greater after warm-up than before warm-up. For positional variability in the AP axis we found no significant main effects. There was a significant 3-way interaction between Warm-Up, Stance Width, and Group, $F(3, 34) = 3.73$, $p = .034$, partial $\eta^2 = 0.180$ (Figure 4).

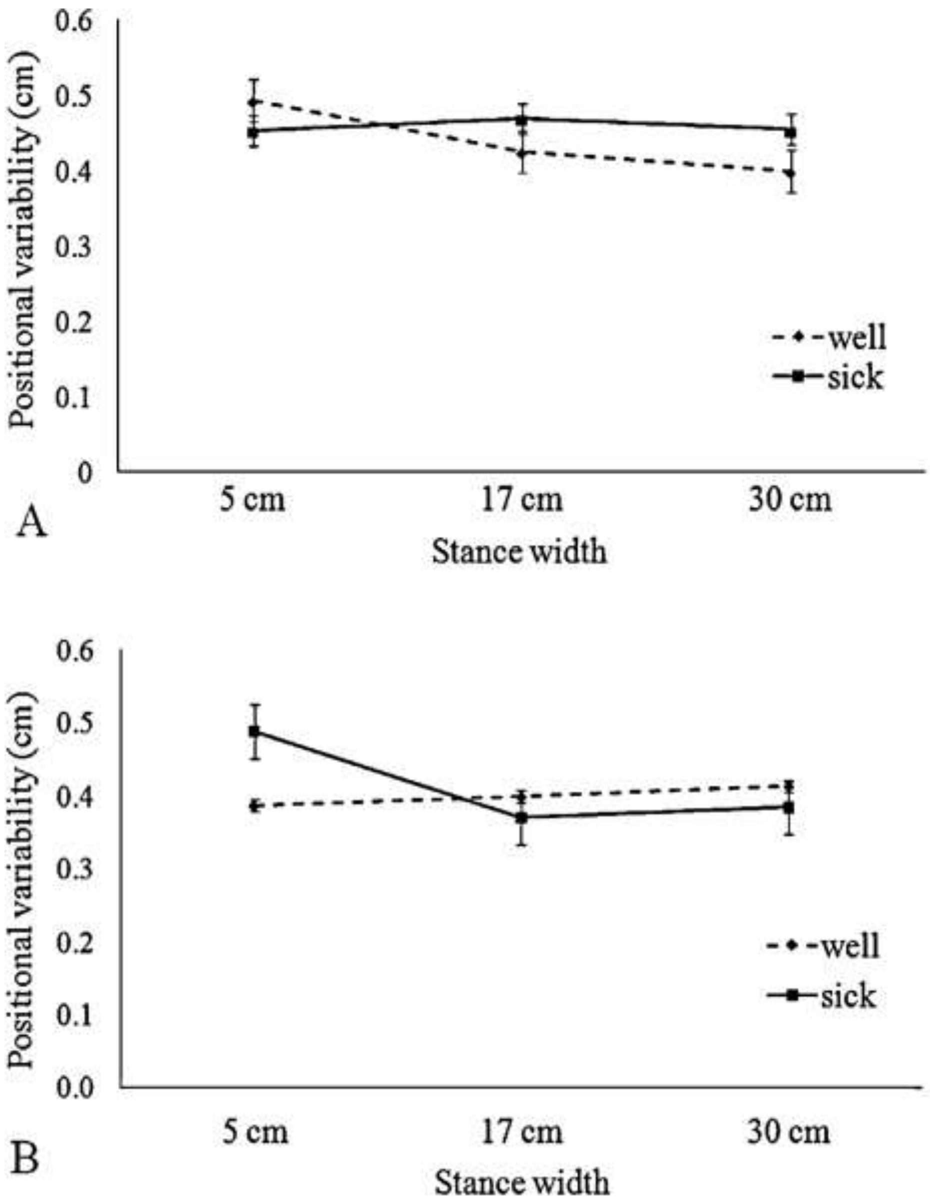

Fig. 4. Significant warm-up x stance width x group interaction for positional variability in the AP axis. (A) Before warm-up. (B) After warm-up. Error bars illustrate standard error of the mean.

Post-hoc tests revealed that the Well and Sick groups differed for each stance width, both before and after warm-up, each $p < .05$. For α of DFA in the ML axis we found significant main effects of Warm-Up, $F(1, 17) = 9.30$, $p = .007$, partial $\eta^2 = .354$ (before warm-up mean = 1.44, SD = 0.01; after warm-up mean = 1.39, SD = 0.02), and Stance Width, $F(1,17) = 3.98$, $p = .028$, partial $\eta^2 = .190$ (5 cm mean = 1.40, SD = 0.01; 17 cm mean = 1.42, SD = 0.01; 30 cm mean = 1.43, SD = 0.01), and a significant Task × Stance Width interaction, F(2, 34) = 8.78, p = .001, partial η_2 = .341 (Figure 5).

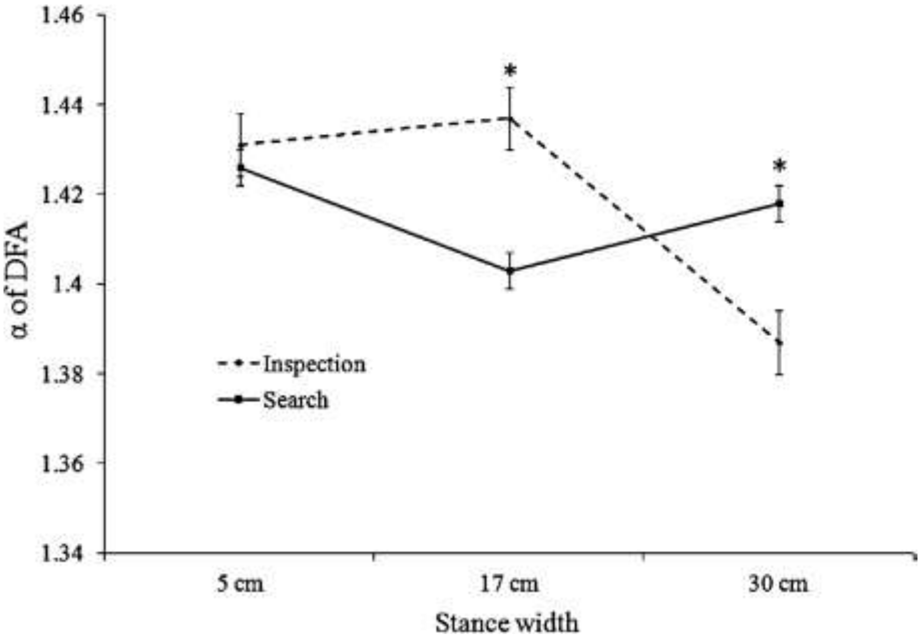

Fig. 5. Significant task x stance width interaction for α of DFA in the ML axis. Error bars illustrate standard error of the mean.

In the 5 cm stance width condition temporal dynamics did not differ between the Inspection and Search tasks. In the 17 cm stance width condition the self-similarity of COP trajectories was greater during performance of the Inspection task than during performance of the Search task, while in the 30 cm stance width condition this pattern was reversed. For α of DFA in the AP axis we found significant main effects of Stance Width, F(2,34) = 52.90, p < .001, partial η_2 = .757 (5 cm mean = 1.11, SD = 0.02; 17 cm mean = 1.29, SD = 0.01; 30 cm mean = 1.41, SD = 0.02), and task, F(1,17) = 15.81, p = .001, partial η_2 = .482 (Inspection task mean = 1.24, SD = 0.01; Search task mean = 1.29, SD = 0.01).

Discussion

In a sample of adolescent boxers, we evaluated pre-bout cognitive performance and standing body sway in relation to reports of post-bout motion sickness. We found differences in pre-bout cognitive performance and body sway between adolescent boxers who reported post-bout motion sickness and those who did not. In addition, we found that cognitive performance was influenced by pre-bout warm-up exercises (Lambourne, and Tomporowski, 2010). Finally, body sway was influenced by pre-bout warm-up exercises, by stance width, and by cognitive tasks engaged in during stance.

Narrow stance width is associated with greater sway, and wider stance width is associated with reduced sway (Day, et al., 1993; Yu, Chung, Hemingway, & Stoffregen, 2013). We have found similar effects in adult boxers (Chen, et al., 2012). In the present study, we replicated these effects in adolescent boxers: In the ML axis the positional variability of the COP was greater for narrow stance width, and was reduced for wider stance width. We also found that stance width influenced the temporal dynamics of sway, with narrow stance being associated with greater predictability or self-similarity of sway (Chen, et al., 2012; Yu, et al., 2013). Cognitive tasks routinely influence standing body sway (Woollacott, et al., 2002). We found a main effect of cognitive tasks on the temporal dynamics of sway (α of DFA). In the AP axis, self- similarity was greater during performance of the Search task than during performance of the Inspection task. In healthy elderly adults, Koslucher et al., (2012) found a similar effect using the same cognitive tasks. In the ML axis, we found a task * stance width interaction for α of DFA (Figure 5); a similar interaction has been observed in pregnant women (Yu, et al., 2013). Taken together, these results indicate that effects of stance width and cognitive task on body sway in adolescent boxers were similar to effects that have been observed in the general population.

Before entering the ring, performance on the search task differed between the Sick and Well groups (Figure 2). Ours is the first study to demonstrate that post-bout motion sickness may be related to pre-bout differences in cognitive performance. Previously, researchers have assumed that variations in cognitive performance would follow concussion, rather than preceding it (Loosemore, et al., 2007). We also found that pre-bout body sway differed between the Well and Sick groups (Figure 4). Previous studies have found that concussions sustained during bouts lead to changes in post-bout body sway (Cavanaugh, et al., 2005). Our results confirm that data on pre-bout body sway may contribute to prediction of post-bout symptoms (Chen, et al., 2012) and extend this finding to adolescent boxers. Before warm-up, participants who reported post-bout motion sickness moved less (in the AP axis) than non-sick participants in the 5 cm stance width condition, and more in the 17 cm and 30 cm conditions. After warm-up, this pattern was reversed. This interaction indicates a complex relationship between motion sickness susceptibility and both biomechanical factors (stance width) and physiological factors (arousal). In adult boxers, warm-up was associated with increased sway in boxers who reported post-bout motion sickness but this relationship was not influenced by stance width (Chen, et al., 2012). Additional research is needed in both adolescents and adults to clarify factors that affect relations between post-bout motion sickness and pre-bout body sway, as well as developmental changes in those factors.

Like many athletes, boxers are at risk for concussion (Moriarity, et al., 2012; Galetta, Barrett, Allen, Madda, and Delicata, et al., 2011). Concussion is associated with nausea

(Erlanger, et al., 2003), and with changes in cognitive performance (Moriarity, et al., 2012), and body sway (Cavanaugh, et al., 2005). Given the results of the present study these facts suggest that pre-bout cognitive performance and body sway may be related to susceptibility to concussion in adolescents. In future research it will be important to examine possible relations between pre-bout measures of cognition and body sway, post-fight motion sickness-like symptoms, and adolescent concussion. None of our adolescent participants had ever been diagnosed with a concussion.

However, pre-bout cognitive and postural effects might indicate lingering effects of earlier sub-concussive head trauma. This hypothesis is compatible with the fact that pre-bout cognitive performance was lower for the Sick group than for the Well group. Further research is needed to understand whether pre-bout differences in cognitive performance and body sway reflect lingering effects of earlier sub-concussive head trauma, or indicate inherent relations between these phenomena and susceptibility to motion sickness and/or concussion. For example, it would be useful to evaluate cognitive performance and body sway in athletes who had never sustained any head trauma (e.g., novices) and to compare these data to subsequent reports of head trauma and motion sickness. If motion sickness is a movement disorder (Stoffregen, 2011), then the effects observed in the present study may implicate relations between cognition, motor control, and susceptibility to neurological injury following head trauma. In general terms, this idea is consistent with research in clinical populations that has documented relations between body sway and cognitive performance in children (Chang, et al., 2012; Chen, et al., 2011). Both concussive and sub-concussive head trauma can have long-term consequences in adolescent athletes (Browne, et al., 2006), a finding which highlights the clinical value of developing objective predictors for susceptibility to head trauma and its sequelae.

Chapter 4

Precursors of post-bout motion sickness in adolescent female boxers

Yi-Chou Chen [a] Tzu-Chiang Tseng [b] Ting-Hsuan Hung [c] & Thomas A. Stoffregen [a]

a. School of Kinesiology, University of Minnesota

b. Graduate Institute of Sport Coaching Science, Chinese Cultural University, Taiwan

c. Office of Institutional Research, Edgewood College, United States

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Corresponding Author:

Thomas A. Stoffregen

tas@umn.edu

Voice: 1-612-626-1056

Fax: 1-612-626-7700

Precursors of post-bout motion sickness in adolescent female boxers

Abstract

Athletic head trauma (both concussive and sub-concussive) is common among adolescents. Head trauma often is followed by motion sickness-like symptoms, by changes in cognitive performance, and by changes in standing body sway. We evaluated adolescent female boxers who did and did not report motion sickness after a bout, together with a control group of non-boxers. We asked whether pre-bout body sway would differ between boxers who experienced post-bout motion sickness and those who did not. In addition, we asked whether pre-bout cognitive performance would differ between non-boxers and boxers with and without post-bout motion sickness. Seven of twenty boxers reported motion sickness after a bout. Pre-bout measures of cognitive performance and body sway were different in boxers who reported post bout motion sickness than in boxers without post-bout sickness, or controls. The results suggest that susceptibility to motion sickness-like symptoms in adolescent female boxers may be manifested in characteristic patterns of body sway and cognitive performance. It may be possible to use pre-bout data to predict susceptibility to post-bout symptoms.

Introduction

Athletic concussion is a growing problem, with as many as 3,000,000 sports-related concussions per year (e.g., Langlois, Rutland-Brown, & Wald, 2006). However, recent research suggests that injuries can be sustained as a result of head trauma that is sub-concussive. The severity of head trauma is a continuum, rather than being a simple dichotomy between concussive and sub-concussive impacts. Just as there are variations in the severity of concussive head trauma there is not a clear line between concussive and sub-concussive head trauma. Sub-concussive athletic head trauma is associated with a diverse set of phenomena. In the present study, we addressed three of these (cognitive performance, nausea or motion sickness, and standing body sway) in the context of adolescent female boxers. Changes in cognitive performance have been documented following sub-concussive head trauma (e.g., Killam et al., 2005; Moriarity et al., 2012; Talavage et al., 2013). Two of the most common early symptoms of head trauma are dizziness and nausea (Erlanger et al., 2003). Self-reports of motion sickness are common among boxers after boxing matches (also known as bouts), with or without a diagnosis of concussion (Ohhashi et al., 2002). Finally, sub-concussive head trauma is associated with changes in control of the body, especially in relation to postural sway (e.g., Parker, Osternig, van Donkelaar, & Chou, 2008).

Sport participation is most common among adolescents (i.e., post-purbertal children) and, in part for this reason head injury is more common among adolescents than other age groups (Loosemore et al., 2007). Many studies have examined phenomena relating to head trauma in adults (Ohashi et al., 2002), or in mixed adult-adolescent samples (Barr & McCrea, 2001). Few studies have focused on sub-concussive head trauma in adolescents.

Adolescent head trauma shares many features between boys and girls, but there are some sex differences (e.g., Frommer et al., 2011), and possible sex differences have been highlighted as a critical research question (McCrory et al., 2009). In the present study, we focused on female boxers.

Precursors of sub-concussive head trauma

Researchers have attempted to identify risk factors for concussion. Existing analyses have focused on epidemiological risk factors, such as age, sex, sport, and previous injuries (e.g., Guskiewiz & McLeod, 2011). Few studies have examined possible risk factors for sub-concussive head trauma. Fewer still have considered the possibility that it might be possible to predict the risk of future head injuries in individuals. We evaluated the hypothesis that symptoms of sub-concussive head trauma might be preceded by distinctive patterns of postural activity and cognitive performance. In earlier studies, we evaluated postural activity and cognitive performance in boxers immediately before bouts. In adult males, pre-bout postural sway differed between boxers who reported post-bout motion sickness and those who did not (Chen et al., 2012). In adolescents (predominately male) pre-bout measures of both postural sway and cognitive performance differed between boxers who reported post bout motion sickness and those who did not (Chen et al., 2013). Those studies focused exclusively on post-bout motion sickness as an indicator of head trauma. In the present study we included a measure of more general head trauma symptoms. We used a version of Graded Symptoms Checklist, or GSC. The GSC is commonly used for early assessment of head trauma in children and adolescents (e.g., Grubenhoff et al., 2010) and in college football players (McCrea et al., 2005).

In the general population, standing body sway is influenced by variations in visual and cognitive tasks such as auditory reaction time, or visual task difficulty (Woollacott & Shumway-Cook, 2002). For example, sway magnitude is often reduced during performance of demanding tasks, such as reading, relative to sway during less demanding tasks, such as looking at a blank target (Chang, Wade, Stoffregen, Hsu, & Pan, 2010; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Yu, Chung, Hemingway, & Stoffregen, 2013). In previous studies, we have found similar effects in boxers (Chen et al., 2012, 2013).

Accordingly, in the present study we predicted that the magnitude and self-similarity of postural sway would be reduced during performance of a demanding visual task in female adolescent boxers when tested before a bout.

The present study

We used subjective reports of post-bout motion sickness to classify adolescent female boxers into two groups; well boxers, and sick boxers. Using this empirical grouping, we evaluated relations between warm-up and cognitive tasks on pre-bout postural sway and cognitive performance. We also compared boxers against a control group of non-boxer adolescent females. We predicted that pre-bout sway would differ between boxers and non-boxers. Based on the results of Chen et al., (2012, 2013), we predicted that pre-bout sway would differ between well boxers and sick boxers. Based on the results of Chen et al., (2013), we predicted that pre-bout cognitive performance would differ between well boxers and sick boxers. The current study resembled Chen et al., (2013), with the following differences. First, whereas in Chen et al., 84% of participants were male in the present study all participants were female. Second, in Chen et al., all participants were boxers, whereas in the present study we also included a control group of non-boxers, which allowed us to make the first comparisons of the quantitative kinematics of postural sway between boxers and non-boxers. Third, unlike Chen et al., (2013), in the present study we did not vary the position of the feet during postural testing. Finally, in addition to standard measures of motion sickness symptoms in the present study we separately evaluated generalized symptoms of head trauma using a version of the Graded Symptoms Checklist (GSC).

Method

Testing was conducted during a multi-school sparring event at the Yingge Vocational High School, New Taipei, Taiwan. Boxing was supervised by three referees and a ringside physician.

Participants

Participants were 32 female adolescents, with mean age 15.15 years, mean height 1.59 m, and mean weight 51.2 kg. Twenty were boxers (with boxing experience from 2 to 7 years) and 12 were non boxers. None of the participants had any diagnosed neurological conditions, and none had ever been diagnosed with a concussion.

Apparatus

Data on postural activity were collected using a Nintendo Wii Balance Board. The Wii Balance Board has response characteristics that are less precise than some purpose built clinical devices, and may not be appropriate for use in clinical diagnosis. However, it has been validated in the context of relative measurements across experimental conditions (Bartlett, Ting, & Bingham, 2014; Clark et al., 2010; Koslucher et al., 2012). We recorded the kinematics of the center of pressure (COP), sampled at 60 Hz in the AP and ML axes.

Procedure

We evaluated motion sickness incidence via a forced-choice, yes/no question, Are you motion sick? Boxers were assigned to Well and Sick groups based solely on their post-bout responses to this forced-choice question. We evaluated the severity of motion sickness symptoms using the Simulator Sickness Questionnaire, or SSQ (Kennedy et al., 1993). The SSQ is a standardized questionnaire that assesses the severity of 16 different symptoms (e.g., nausea, disorientation), which was translated into Chinese. We evaluated head trauma-related symptoms using the GSC. We used a 26-item version of the GSC (Faure & Pemberton, 2010). We measured body sway as participants stood on a force plate.

Participants stood with their feet on marked lines such that the midlines of the heels were 17 cm apart and the feet were at an angle of 10^o relative to one another. For postural testing the duration of each trial was 60 s. During trials, participants performed one of two cognitive tasks; Inspection or Search. Each testing session comprised three trials in each task condition for a total of 6 trials per session. Within testing sessions the order of conditions was counterbalanced across participants. Targets for the cognitive tasks were sheets of white paper 13.5 cm × 17 cm mounted on rigid cardboard (Chen et al., 2012). In the Search task the target was one of four blocks of English text, each comprising 13 or 14 lines of text printed in a 12-point sans serif font. Prior to each trial the participant was given a target letter (A, R, N, or S) and asked to count the number of times the target letter appeared in the text. After each trial, participants reported the number of letters counted. In the Inspection task, the target was a blank sheet of white paper; participants were instructed to keep their gaze within the borders of the target.

Boxers were tested three times; before warm-up, after warm-up, and immediately after completing their bout; accordingly, they participated in a total of 18 trials of postural testing. Non-boxer control participants were tested twice; before and after warm-up; accordingly, they participated in a total of 12 trials of postural testing. In the first testing session participants completed the informed consent procedure and responded to the forced-choice question about motion sickness status, after which they completed SSQ-1, GSC-1, and the first six postural trials. This was followed by the warm-up. For all participants, warm-up activities lasted approximately 30 minutes. Boxers used a standard pre-bout warm-up protocol, which included jogging, stretching and shadow boxing. Non-boxer control participants engaged in jogging and stretching. Immediately after warm-up participants responded to the forced-choice question about motion sickness status, after which they completed SSQ-2, GSC-2, and the second set of six postural trials.

Boxing was conducted under the rules of the International Boxing Association (AIBA) for female boxers. Bouts had up to three 2-minute rounds, with a 1-minute break between rounds. Bouts were monitored by AIBA-certified referees and a ringside physician. Bouts could be terminated early by the referee. For boxers, the third testing session (forced-choice statement of motion sickness status, SSQ-3, GSC-3, and the third set of 6 postural trials) was conducted within 20 minutes after bouts.

Data Analysis

For symptom severity we used the Total Severity Score of the SSQ. SSQ data are not normally distributed and, accordingly, were analyzed using non-parametric statistics

(Kennedy et al., 1993). The GSC was scored in the recommended manner (Faure & Pemberton, 2010). We separately evaluated the spatial magnitude and temporal dynamics of postural activity. We assessed the spatial magnitude of postural activity in terms of the positional variability of the COP, which we defined operationally as the standard deviation of COP positions. Measures of the spatial magnitude of movement tend to eliminate or discard data on the temporal structure of movement, that is, data on how the measured quantity varied in time. Analyses that preserve information about the temporal structure of data on human movement (that is, analyses of the temporal dynamics of movement) are increasingly common. We assessed the temporal dynamics of postural activity using detrended fluctuation analysis, or DFA. DFA describes the relation between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured. DFA has been used in several studies of the control of stance (e.g., Lin et al., 2008), and in research on visually induced motion sickness (Dong et al., 2011; Stoffregen et al., 2010), and boxing (Chen et al., 2012, 2013). We conducted inferential tests on α, the scaling exponent of DFA, as derived from the COP data. The scaling exponent is an index of long-range autocorrelation in the data, that is, the extent to which the data are self-similar over different time scales.

White noise, which is uncorrelated, yields $\alpha = .5$. The presence of long-range autocorrelation is indicated by $\alpha > .5$. Pink noise (also known as 1/f noise) is indicated when $\alpha = 1.0$. Values of $\alpha > 1.0$ indicate non-stationary activity that resembles a random walk, while $\alpha > 1.5$ indicates Brownian noise. Quiet stance in healthy adults tends to be non-stationary typically yielding $1.0 > \alpha > 1.5$. We did not integrate the time series before performing DFA. We conducted separate analyses of postural activity before and after bouts. Analyses of postural activity before bouts allowed us to compare boxers and non-boxer controls, and to ask whether postural activity before bouts was related to post-bout motion sickness status.

Results

Motion sickness incidence and severity

Both before and after warm-up, each participant stated that they were not motion sick. After bouts, 13 boxers stated that they were not motion sick and were included in the Well Boxer group. Of these, 9 won their bouts and 4 lost. After bouts, seven boxers stated that they were motion sick, and were included in the Sick Boxer group. Of these, 1 won her bout and 6 lost. We evaluated the severity of motion sickness symptoms using the total severity score from the SSQ. These scores are summarized in Table 1. Before warm-up, SSQ-1 total severity scores did not differ between the well boxers and non-boxer controls, two-tailed Mann-Whitney U = 79, p = .43, between the sick boxers and the controls, U = 65, p = .06, or between the well boxers and the sick boxers, U = 29.5, p = .22. After warm-up, SSQ-2 scores also did not differ between the well boxers and controls, U = 44, p = .07, between the sick boxers and the controls, U = 36.5, p = .67, or between the well boxers and the sick boxers, U = 50, p = .75. After boxing, SSQ-3 scores were higher among sick boxers than among well boxers, U = 87, p = .001.

Graded Symptoms Checklist

GSC scores are summarized in Table 1. Before warm-up, GSC-1 scores did not differ between the well boxers and non-boxer controls, two-tailed Mann-Whitney U = 69.5, p = .66, between the sick boxers and the controls, U = 24, p = .14, or between the well boxers and the sick boxers, U = 61, p = .23. After warm-up, GSC-2 scores also did not differ between the well boxers and controls, U = 77.5, p = 1.0. However, GSC-2 scores were greater among sick boxers than among controls, U = 7.0, p = .001, and were greater among sick boxers than among well boxers, U = 73, p = .03. After boxing, GSC-3 scores were higher among sick boxers than among well boxers, U = 68.5, p = .03.

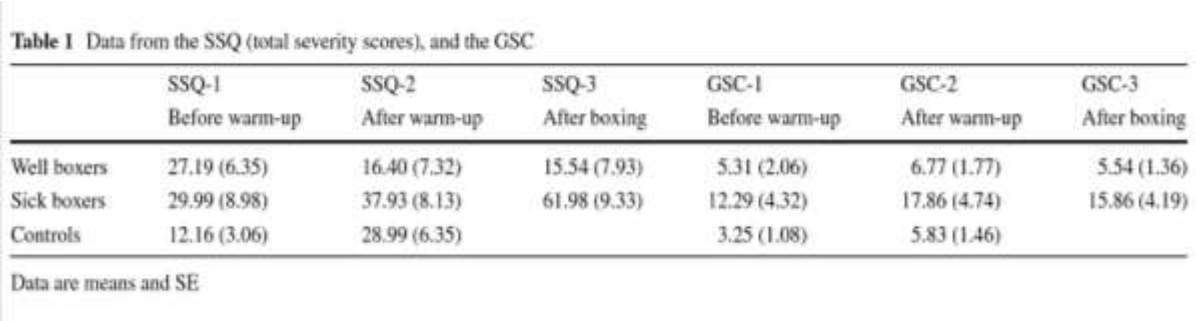

Table 1 Data from the SSQ (total severity scores), and the GSC

	SSQ-1 Before warm-up	SSQ-2 After warm-up	SSQ-3 After boxing	GSC-1 Before warm-up	GSC-2 After warm-up	GSC-3 After boxing
Well boxers	27.19 (6.35)	16.40 (7.32)	15.54 (7.93)	5.31 (2.06)	6.77 (1.77)	5.54 (1.36)
Sick boxers	29.99 (8.98)	37.93 (8.13)	61.98 (9.33)	12.29 (4.32)	17.86 (4.74)	15.86 (4.19)
Controls	12.16 (3.06)	28.99 (6.35)		3.25 (1.08)	5.83 (1.46)	

Data are means and SE

Search task performance

Before boxing. The data are summarized in Figure 1. We evaluated performance on the Search task in terms of the number of target letters counted as a percentage of the total number of target letters in the stimulus texts. We conducted a 2 (before warm-up vs. after warm-up) × 3 (controls vs. well boxers vs. sick boxers) ANOVA on the percentage of target letters counted. Performance was better after warm-up (mean = 88.47%, SD = 1.40%) than before warm-up (mean = 80.49%, SD = 1.52%), F (1, 29) = 32.50, p < .001, partial η_2 = .528. In addition, the main effect of groups was significant, F (2, 29) = 3.93, p = .03, partial η_2 = 0.213. Post-hoc tests (multiple comparisons) revealed that performance among sick boxers was lower than in well boxers, p = .03, or controls, p = .01, which did not differ from each other.

After boxing. Boxing led to a decline in performance on the search task (mean = 77.82%, SD = 10.11%), relative to performance after the warm-up (mean = 87.70%, SD = 8.45%), t = 3.36, p < .001./After bouts, performance did not differ between well boxers (mean = 79.40%, SD = 10.52%) and sick boxers (mean = 74.88%, SD = 9.30%), t = 0.95, p = .17.

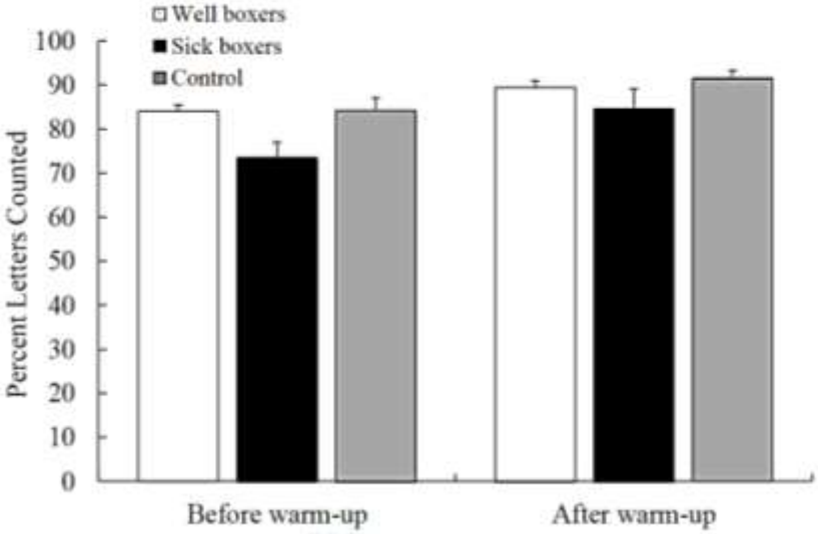

Figure 1. Performance on the search task (percent of target letters counted) before and after warm-up for non-boxer controls and for boxers who did (sick) and did not (well) report motion sickness after boxing. The error bars represent the standard error of the mean.

Postural activity before boxing

For postural activity before bouts we conducted 2 (Inspection vs. Search) × 2 (Before warm-up vs. After warm-up) × 3 (Well Boxers vs. Sick Boxers vs. Controls) ANOVAs on positional variability of the COP and α of DFA in the AP and ML axes. Postural activity for the three groups is summarized in Figure 2.

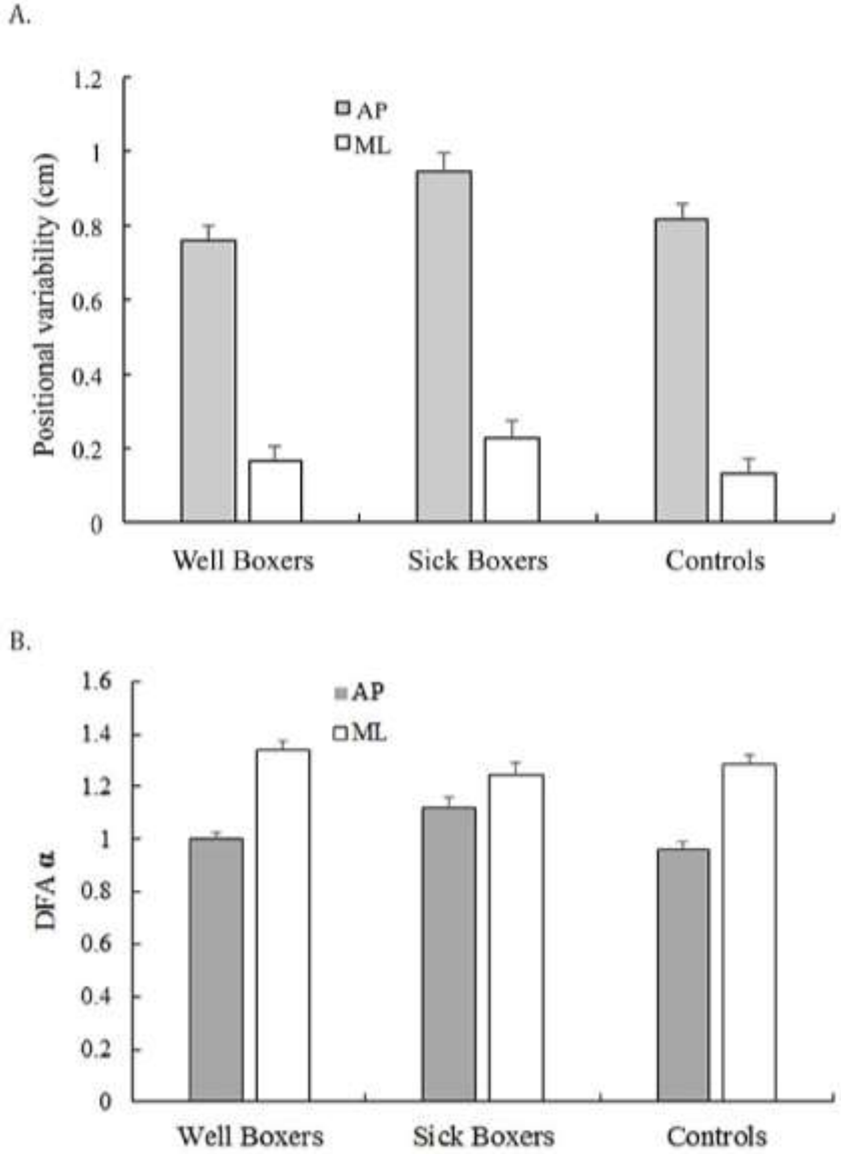

Figure 2. Postural activity for well boxers, sick boxers, and non-boxer controls in the anterior-posterior (AP) and medio-lateral (ML) axes. A. Positional variability of the COP. B. Temporal dynamics (α of DFA) of COP positions. The error bars represent the standard error of the mean.

Effects of cognitive task. Positional variability of the COP in the AP axis was reduced during performance of the search task (mean = 0.79, SD = 0.04) relative to sway during performance of the inspection task (mean = 0.89, SD = 0.04), F (1, 29) = 9.52, p = .004, partial η2 = .247. In the ML axis, positional variability of the COP also differed between cognitive tasks, F (1, 29) = 6.70, p = .015, partial η_2 = .188; however, sway was greater during performance of the search task (mean = 0.20, SD = 0.02) than during performance of the inspection task (mean = 0.16, SD = 0.01). For the temporal dynamics of COP positions in the AP axis, there were no significant effects relating to cognitive tasks. In the ML axis, self-similarity was greater during performance of the inspection task (mean α = 1.33, SD = 0.02) than during performance of the search task (mean α = 1.25, SD = 0.03), F (1, 29) = 7.61, p = .01, partial η_2 = .21. Effects of warm-up. For positional variability in the AP axis the interaction between warm-up and cognitive tasks was significant, F (1, 29) = 7.14, p = .012, partial η_2 = .20. Before warm-up, sway did not differ during performance of the inspection (mean = 0.87, SD = 0.05) and search (mean = 0.84, SD = 0.05) tasks, but after warm-up they differed (mean Inspection = 0.91, SD = 0.04; mean Search = 0.74, SD = 0.04). For the temporal dynamics of COP positions in the AP axis, the main effect of warm-up was significant, F (1, 29) = 25.20, p < .001, partial η_2 = .47. The self-similarity of sway after warm-up (mean α =1.09, SD = 0.02) was greater than before warm-up (mean α = 0.97, SD = 0.02). In the ML axis, self-similarity was greater before warm-up (mean α = 1.31, SD = 0.02) than after warm-up (mean α = 1.27, SD = 0.02), F (1, 29) = 5.21, p = .03, partial η_2 = .15.

Sway before boxing in relation to motion sickness after boxing. For positional variability in the AP axis, the interaction between cognitive tasks, warm-up, and groups was significant, F (2, 29) = 4.26, p = .024, partial η_2 = .227. As shown in Figure 3, before warm-up the variation in cognitive tasks had little effect on any group, whereas after warm-up the variation in cognitive tasks preferentially affected sick boxers. After warm-up (Figure 3B), sway during performance of the Inspection task was greater among sick boxers than among well boxers or non-boxer controls. For positional variability of the COP in the ML axis, the main effect of groups was significant, F (2, 29) = 4.55, p = .019, partial η_2 = .239 (Figure 2A). Post-hoc tests (multiple comparisons) revealed that sway among sick boxers was greater than among non-boxer controls, p = .005, but did not differ from well boxers. For the temporal dynamics of sway in the AP axis, we found a significant main effect of groups, F (2, 29) = 5.14, p = .01, partial η_2 = .26 (Figure 2B). Post-hoc tests (multiple comparisons) revealed that self-similarity was greater among sick boxers than among well boxers, p = .02, or controls, p = .004, which did not differ from each other. In addition, the interaction between warm-up and groups was significant, F (2, 29) = 19.11, p < .001, partial η_2 = .57. As shown in Figure 4, warm-up had little effect on self-similarity among well boxers and non-boxer controls, but produced an increase in self-similarity among sick boxers.

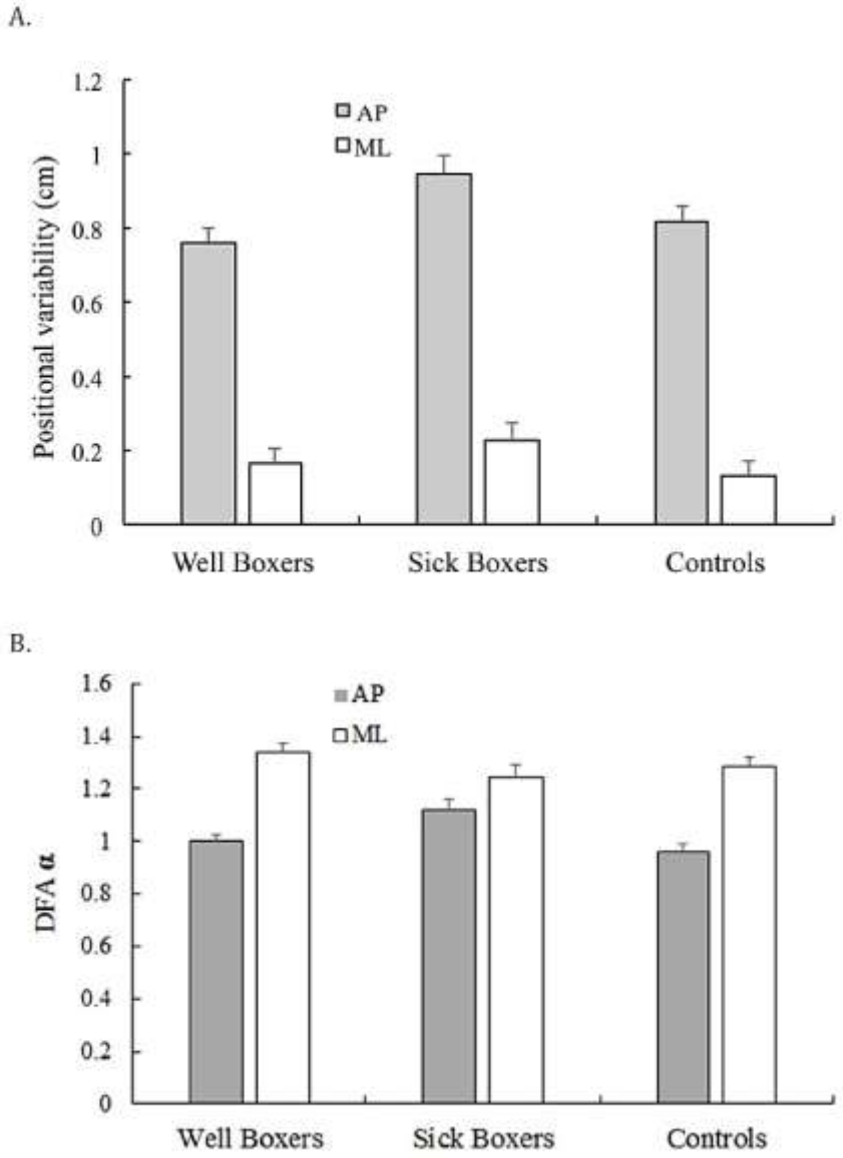

Figure 3. Positional variability of the COP in the AP axis before boxing, illustrating the statistically significant 3-way interaction between cognitive tasks (inspection vs. search), warm-up (before vs. after), and groups (well boxers vs. sick boxers vs. controls). A. Before warm-up. B. After warm-up. The error bars represent the standard error of the mean.

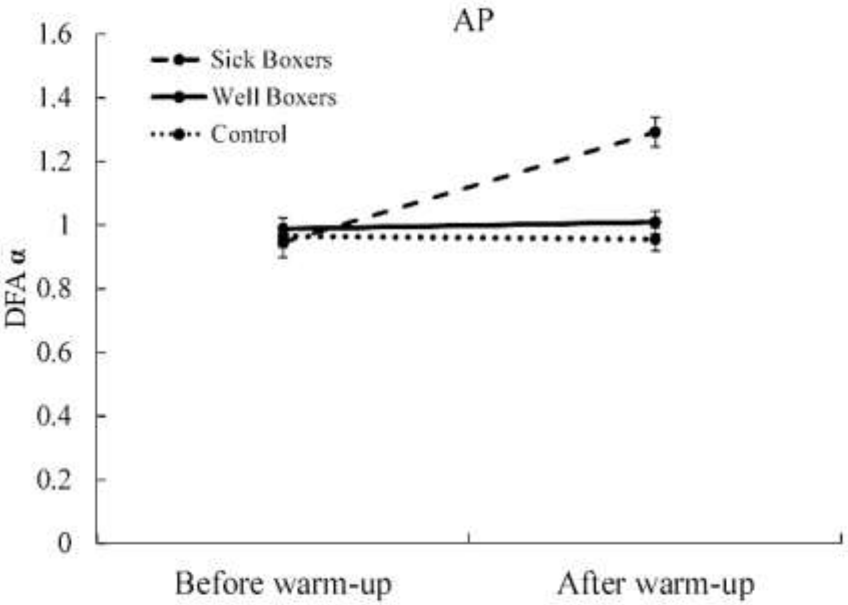

Figure 4. Self-similarity of COP positions in the AP axis before boxing, illustrating the statistically significant interaction between warm-up (before vs. after) and groups (well boxers vs. sick boxers vs. controls). The error bars represent the standard error of the mean.

Postural activity after boxing

Our analyses of postural activity after bouts was limited to boxers, and comprised 2 (Inspection vs. Search) × 2 (Well vs. Sick) ANOVAs on positional variability and α of DFA in the AP and ML axes. We found only one statistically significant effect: In the AP axis positional variability of the COP was greater in the Sick group (mean = 1.03, SD = 0.11) than in the Well group (mean = 0.73, SD = 0.08), F (1, 18) = 4.62, p = .046, partial η_2 = 0.20.

Discussion

We evaluated cognitive performance, postural sway, head trauma-related symptoms, and motion sickness in adolescent female boxers and non-boxer controls before and after a physical warm-up routine and (for boxers) immediately after bouts. After bouts, 7 of 20 boxers stated that they were motion sick. Analysis of pre-bout data revealed that sick boxers differed from well boxers (and from non-boxer controls) before they entered the ring. These pre-bout differences suggest that there may be individual differences in susceptibility to effects of head trauma and that such differences might be identified through non-invasive behavioral measures. After bouts, well boxers and sick boxers exhibited differences in postural sway, and sick boxers reported higher levels of head trauma-related symptoms.

Graded Symptoms Checklist

As expected, before warm-up the three groups had equivalent scores on the GSC. Also as expected, GSC scores after bouts were higher for sick boxers than for well boxers. A novel finding was that, GSC scores after warm-up were higher among boxers who (later) reported post-bout motion sickness. After warm-up, each participant stated that they were not motion sick. In addition, after warm-up, the three groups did not differ in terms of SSQ scores. We can conclude that among boxers who reported post-bout motion sickness the pre-bout warm-up led to an increase in symptoms that were not directly related to motion sickness.

Boxing performance and post-bout motion sickness

The majority of well boxers won their bouts. By contrast, the majority of sick boxers lost their bouts. A similar effect has been observed among players of video games. Stoffregen, Chen, and Koslucher (2014) asked participants to play a video game in which an avatar fought with a variety of assailants. After playing the game for up to 50 minutes some players reported becoming motion sick, while others did not. Before experiencing motion sickness, players in the sick group exhibited lower performance in the game (their avatar was killed more times) than players in the well group. While video games obviously differ dramatically from boxing there may be similarities between them in terms of relations between the stable control of the body, on the one hand, and the ability to perform demanding visual-manual tasks, on the other. Unstable control of body sway leads to unstable control of the head and eyes, which can lead to degraded visual performance (Chen, Tsai, Stoffregen, Chang, and Wade, 2011) and, ultimately to degraded performance in visually guided actions (Haddad, van Emmerik, Wheat, and Hamill, 2008; Haddad, Ryu, Seaman, and Ponto, 2010). It may be that boxers who already had degraded postural control (that is, boxers who were at risk for post-bout motion sickness) were less able to see incoming punches and/or less able to organize and execute defensive responses (e.g., blocks, or leaning away from punches) or offensive actions (punches). This hypothesis can be addressed in future research.

Pre-bout cognitive performance and sway

Cognitive performance was better after warm-up than before warm-up, consistent with Chen et al., (2013) and with the broader literature (Lambourne & Tomporowski, 2010). In addition, before bouts performance on the search task was lower among sick boxers than among well boxers or non-boxer controls. A similar effect was observed in a sample of mainly male adolescent boxers (Chen et al., 2013). Taken together, the two studies suggest that among adolescent boxers susceptibility to post-bout motion sickness may be revealed in pre-bout measures of visual/cognitive performance. Our manipulation of cognitive tasks influenced both the positional variability and the temporal dynamics of sway, consistent with previous studies using the same tasks in boxers (Chen et al., 2013), in healthy elderly adults (Koslucher et al., 2012), and in pregnant women (Yu et al., 2013).

Body sway in boxers versus non-boxer controls

We conducted the first direct comparison of standing body sway in boxers and non-boxer controls. Before bouts, postural sway in well boxers closely resembled sway in non-boxer controls in both spatial magnitude and temporal dynamics (Figure 2). That is, we found no evidence that boxing leads to systematic changes in the control of upright stance.

Pre-bout sway in relation to post-bout motion sickness

Before entering the ring, the postural sway of boxers in the sick group differed from sway in both well boxers and non-boxer controls. Differences were observed in both the spatial magnitude and the temporal dynamics of sway. In a simple main effect, pre-bout sway was more self-similar among boxers who (later) reported post-bout motion sickness than among well boxers or non-boxer controls. Abnormally high levels of self-similarity are associated with a variety of clinical conditions, including Parkinson's disease (Schmit et al., 2006) and bipolar disorder (Bolbecker et al., 2011), as well as visually induced motion sickness (Stoffregen et al., 2010). Taken together, these results appear to be consistent with the “loss of complexity” hypothesis regarding relations between the control of movement and overall health of the nervous system (Vaillancourt and Newell, 2002). In addition, there were complex interactions involving cognitive tasks and warm-up. The physiological arousal arising from the pre-bout warm-up led to changes in body sway that were general across all participants. However, the interactions illustrated in Figures 3 and 4 demonstrate that the warm-up also had effects on body sway that were unique to boxers who reported post-bout motion sickness. The general pattern of results was consistent with previous studies of adult male boxers (Chen et al., 2012) and predominantly male adolescent boxers (Chen et al., 2013). Cavanaugh et al., (2005) and Guskiewicz et al., (2001) found no differences in pre-season postural sway between athletes who later sustained concussions and those who did not. However, those studies evaluated body sway in the context of moving platform posturography. By contrast, we evaluated posture in the absence of any mechanical perturbations to stance. It may be that tests of unperturbed sway are more sensitive measures. However, it is important to recall that none of our participants had ever been diagnosed with a concussion. For this reason, the pre-bout group differences in body sway that we observed cannot be attributed to lingering effects of prior history of concussion. It is possible that pre-bout differences in body sway were related to prior history of sub-concussive head trauma; this may be an important subject for future research. Separately, it would be interesting to apply our methods of postural testing to pre-injury sway in relation to subsequent concussion. Existing research relating biomarkers to concussion focus only on post-hoc relationships, that is, on biomarkers that indicate that a concussion has occurred (e.g., Neselius et al., 2012). Our results, together with those of Chen et al., (2012, 2013) suggest that there may be individual differences in susceptibility to or predisposition for head trauma to give rise to some form of brain injury (either concussive or sub-concussive). We have documented these differences in non-invasive data on postural activity; however, our results may motivate a search for more invasive biomarkers, such as may be found in cerebrospinal fluid.

Conclusion

Possible sex differences in injury arising from head trauma have been highlighted as a critical research question (McCrory et al., 2009). To address this issue we conducted the first study relating prebout measures of postural sway and cognitive performance to post-bout reports of motion sickness in adolescent female boxers. Before bouts, the postural sway and cognitive performance of well boxers closely resembled those of non-boxer controls. By contrast, pre-bout measures revealed that boxers who later reported motion sickness moved differently, and exhibited reduced cognitive performance relative to both well boxers and non-boxer controls. None of our participants had ever been diagnosed with a concussion; accordingly, our results suggest either 1) that uninjured boxers differ as a function their susceptibility to future sub-concussive head injury, or 2) that prior history of sub-concussive head injury alters postural sway and cognitive performance in ways that are predictive of susceptibility to future sub-concussive head injury. In either case, the out results (together with those of Chen et al., 2012; 2013) raise the possibility that there may be individual differences in susceptibility to sub-concussive head injury, and that it may be possible to use simple, non-invasive measures of body sway and cognitive performance to predict susceptibility in individual.

The findings relating pre-bout measures to post-bout motion sickness in sub-concussive head trauma raise questions about whether similar effects may exist in the context of actual concussion. To answer these questions, new research is needed in which pre-bout sway and cognitive performance are evaluated as a function of post-bout concussion status. Comparisons between participants with concussive and sub-concussive head trauma would allow us to ask whether pre-injury postural sway can be used to differentially predict an individual’s susceptibility to these two types of injury.

Chapter 5 General discussion

Results of the Three Experiments

Experiment 1: Cognitive and Postural precursor of motion sickness symptoms of adult male club boxers

For adult club boxers, before competition there was no difference in symptom severity in all participants. After boxing, however, 7 of 15 (47%) boxers reported motion sickness. The total severity scores were higher among participants in the “Sick” group than in the “Well” group. When the boxers were examined after warm-up, none stated they were motion sick. Research statistics showed there were significant main effects on postural variability of Warm-up, Stand width, and Group (in ML axis). These factors of variability suggest a mixture of factors worked together, including a major postural difference between Well and Sick groups. Compared to the Well group, the Sick group had higher positional variability, which suggests that the Sick group may be less adaptable to whole body neuromuscular control before they started boxing. Since the Sick group is less adaptable for postural control, there is little doubt that they will become better during the competition. Therefore, the group may sustain more punishment during the bout, and develop motion sickness symptoms after the bout. Even some of Sick boxers won the bout. These winners may have received “fewer hits” (lower points taken), but were still hit “hard enough.” As a result, they may have developed symptoms throughout the bout. Also, stance width played an important role. The larger the stance width, the better the support for postural control (yield less sway). Larger stance also exists in time series self-similarity (α of DFA) in ML. Visual performance was influenced by stance width as well.

The larger (30 cm vs. 5 cm) the stance width, the better the visual performance. These variations in stance width suggest that when body has better basal (structural) support, the torso may also aid through stabilization and head kinematics, which can then enhance visual performance.

Experiment 2: Cognitive and Postural precursor of motion sickness and concussive symptoms of adolescent boxers

After the findings on the adult club boxers, the second study looked at the cognitive and postural precursor of adolescent boxers (20 male and 4 female). The second study examined if the same clues that were found in young adults also existed in adolescents.

As predicted, in all participants, the symptoms did not appear until boxing, which was synchronized to the first study. Nine participants stated that they were motion sick. The majority of post bout sick participants lost the bout (6 out of 9), while one-third of sickness boxers won the bout (3 out of 9). These findings suggest that Sick boxers had higher percentages of lost bouts. They also developed poorer neuromuscular coordination, which might be attributed to their poorer pre-bout postural variability and letter tracking. On the other hand, ten participants stated that they were not motion sick and were assigned to the Well group. Of these, six won their bouts and four lost.

All participants could count more target letters after warm-up than before warm-up, showing that cognitive performance could be enhanced by physical exercise. In addition, the Well group counted more letters than the Sick group, and they also had better postural control, which might aid pre-bout visual performance. The foundation of postural stance width influenced postural dynamics. For example, the temporal dynamics did not differ between visual tasks (inspection vs. search) in the 5 cm; which might indicate that narrower basal support (e.g. 5 cm) did not help postural sway on visual demanding tasks. However, the temporal dynamics of COP trajectories were reduced at 17 cm during the search task, suggesting that a proper stance width (e.g. 17 cm) supported the postural control and the visual performance in the specific search tasks.

Experiment 3: Cognitive and Postural precursor of motion sickness and concussive symptoms of adolescent female boxers

Finally, a group of teenage female adolescent boxers (n = 20), and the same age female control group (n = 12) were recruited for the third study. A widely accepted concussion Graded Symptoms Checklist (GSC) was used for monitoring head trauma. Before and after warm-up no participants stated that they were motion sick or had signs of concussion. After bouts, thirteen boxers stated that they were not motion sick, and were included in the Well group. Of these, nine won their bouts and four lost. Seven boxers stated that they were motion sick, and were included in the Sick group. Of these, one won her bout and six lost, suggesting that female boxers (e.g. Sick group) who received more hits, and lost the bout might be related to the onset of concussive symptoms. However, in this group, poorer postural control and cognitive performance were detected before bout, and this might be the reason why they received more hits, or suffered stronger hits during the bout. The GSC concussive symptoms were higher among Sick boxers than Well boxers at post warm-up and post bout, which closed to the total severity scores (Chen, et al, 2013). This trend was found in the same group of Sick boxers in SSQ, suggesting the importance of symptom-based evidence, which is shared by different questionnaires (SSQ and GSC).

Overall Summary

Through three experiments that contained different ages, gender and postural variations, a series of original studies relating pre-bout measures of postural sway and cognitive performance to post-bout motion sickness and concussive symptoms in adult, adolescents, and adolescent female boxers were conducted. These studies, provide new insights that might be useful in monitoring postural control in athletes through affordable tools in athletic training, or develop monitoring system of physical conditioning. These experiments suggest:

1). A 25 to 30 minute moderate-to-intense warm-up might trigger hidden cognitive and postural precursors which were found in "Sick" boxers who later reported motion sickness and concussive symptoms after boxing competition.

2). These studies provided simple, non-invasive methods through pre-competition postural sway and cognitive performance, which might be useful to prevent sport-related concussion or sub-concussive head injury.

3). There might be a prior history of sub-concussive head injury in sick participants, not necessary detected, and evaluated by doctors, which alters pre-bout postural sway and cognitive performance in ways that are predictive of susceptibility to future sub concussive head injury. If this is the case, it seems this prior history could be detected before competition.

4). Increased pre-bout postural sway and declined cognitive performance may be linked to decreased neuromuscular coordination in people who have poorer perception and action coupling. There might be some other non-visible problems that influenced postural control of the Sick group before competition, and caused Sick boxers to suffer from high frequencies of hits, and stronger quality of hits in the form of stronger hits, during the bout. Luckily, these problems can be detected through postural sway.

Theoretical Conclusion

In a series of three experiments in the field, I tested the presumptions of the ecological theory of postural instability of motion sickness. The pre-bout abnormal sway, and cognitive performance that was based on the post-bout motion sickness and concussive symptoms were evaluated. These turned out to be a very successful strategies. These strategies differed from current concussion and postural sway studies. The majority of researchers evaluated post-concussion symptoms, or researched individuals who have a history of concussion. The design of my study does not do this.

There may be multiple sources that triggered postural instability and cognitive decline before boxing competitions. These sources could be psychological or physiological, or a mixture of both. Overall, the increased postural variability and cognitive decline could be the expressions of these sources and detected in three studies of this dissertation. Another important theoretical benefit of early detection is, after vigorous sports competition, there may be too many noises generated in the biological system (human body). In that case, there might be more complicated signals that need to be handled. With this pre-competition evaluation, those noises might be minimized.

The concepts between COP variability and DFA time series

I separately evaluated the magnitude and temporal dynamics of postural activity. Magnitude measures, such as positional variability, velocity, and range, provide information about the size or spatial extent of movement (e.g., ‘‘by how many centimeters do COP data points tend to differ from each other?’’). Magnitude measures, by their nature, tend to eliminate or discard the temporal structure of movement data, that is, how the measured quantity varies in time (e.g., ‘‘to what extent does COP displacement at time A resemble displacement at time B?’’). Spatial magnitude differs qualitatively from temporal patterns and for this reason measures of spatial magnitude are not analogous to measures of temporal dynamics; one is not a version of, or substitute for the other. It is for this reason that I evaluated spatial magnitude and temporal dynamics separately.

Implications for Practice and Future Studies

In the future, it would be valuable to measure pre competition postural sway and cognitive performance to concussive biomarkers or individuals who are actually diagnosed as concussed patients.

Through this methodology it may be valuable for coaches or athletic trainers to evaluate the pre-competition sway patterns and cognitive performance for athletes, without the need of a concussion history. For example, coaches can compare athletes’ regular sway patterns (logs) and compare to athletes’ pre-competition sway patterns and visual performances. Also, it may be useful that athletes themselves can use postural sway as a precursor of other psycho-physiological maladies (e.g. over training and stress responses,) during their training seasons. To do so, each individual could collect a series of their own sway data (daily) through Wii balance board or mobile applications, such as physical toolbox in the Android system, or iSeismometer in the iOS system, and compare their average sway patterns to pre-competition patterns.

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APPENDIX A

姓名：　　　　　　　　　　　　　　　　　**前測**
日期：

您此時是否感到暈眩？請圈選右邊選項：　　是　　否

請根據以下等級說明，圈選您現在的感覺（數字）。

0 = 無任何影響，**1** = 輕微，**2** = 中度，**3** = 嚴重

1. 整體不適感	0	1	2	3
2. 疲勞	0	1	2	3
3. 頭痛	0	1	2	3
4. 眼睛不適	0	1	2	3
5. 注意力難集中	0	1	2	3
6. 唾液分泌增加	0	1	2	3
7. 流汗	0	1	2	3
8. 感到噁心	0	1	2	3
9. 注意力不集中	0	1	2	3
10. 頭昏腦脹	0	1	2	3
11. 視覺模糊	0	1	2	3
12. 頭昏眼花（睜眼）	0	1	2	3
13. 頭昏眼花（閉眼）	0	1	2	3
14. 失去方向感	0	1	2	3
15. 輕度噁心	0	1	2	3
16. 打嗝	0	1	2	3

SSQ_1

姓名：　　　　　　　　　　　　　　　　**後測**

編號：

您此時是否感到暈眩？請圈選右邊選項：　　是　　否

請根據以下等級說明，圈選您現在的感覺（數字）。

0 = 無任何影響，**1**= 輕微，**2** = 中度，**3** = 嚴重

1. 整體不適感	0	1	2	3
2. 疲勞	0	1	2	3
3. 頭痛	0	1	2	3
4. 眼睛不適	0	1	2	3
5. 注意力難集中	0	1	2	3
6. 唾液分泌增加	0	1	2	3
7. 流汗	0	1	2	3
8. 感到噁心	0	1	2	3
9. 注意力不集中	0	1	2	3
10.頭昏腦脹	0	1	2	3
11.視覺模糊	0	1	2	3
12.頭昏眼花（睜眼）	0	1	2	3
13.頭昏眼花（閉眼）	0	1	2	3
14.失去方向感	0	1	2	3
15.輕度噁心	0	1	2	3
16.打嗝	0	1	2	3

姓名：　　　　　　　　　　　　　　**家測**

編號：

您此時是否感到暈眩？請圈選右邊選項：	是	否
若此時感到暈眩，請說明您何時察覺？	時間：	日期：

請根據以下等級說明，圈選您現在的感覺（數字）。

0 = 無任何影響，**1**= 輕微，**2** = 中度，**3** = 嚴重

1. 整體不適感	0	1	2	3
2. 疲勞	0	1	2	3
3. 頭痛	0	1	2	3
4. 眼睛不適	0	1	2	3
5. 注意力難集中	0	1	2	3
6. 唾液分泌增加	0	1	2	3
7. 流汗	0	1	2	3
8. 感到噁心	0	1	2	3
9. 注意力不集中	0	1	2	3
10. 頭昏腦脹	0	1	2	3
11. 視覺模糊	0	1	2	3
12. 頭昏眼花（睜眼）	0	1	2	3
13. 頭昏眼花（閉眼）	0	1	2	3
14. 失去方向感	0	1	2	3
15. 輕度噁心	0	1	2	3
16. 打嗝	0	1	2	3

SSQ_3

Graded Symptom Checklist 姓名：________________________ 日期：

無徵狀		**中度**			**嚴重**	
0	1	2	3	4	5	6

請根據以下徵狀填入上列分數

徵狀	**基準線**	**剛比賽完**	**賽後 24 小時**	**賽後 三天**	**賽後 四天**	**賽後 五天**
視覺模糊						
頭暈						
倦怠						
睡得更多						
容易分心						
疲勞						
如處在霧中						
感覺變慢						
頭痛						
不尋常的傷感						
易怒						
失去意識						
失去方向感						
記憶出問題						
噁心						
神經質						
性格改變						
平衡變差						
耳鳴						
感到悲傷						
眼冒金星						
對光敏感						
對噪音敏感						
睡眠受干擾						
兩眼無神						
嘔吐						
總分						