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博士（スポーツ科学）

A kinematic analysis of shoulder and torso during front crawl swimming and its implications to overuse injuries

クロール泳における肩複合体と腰部の 3 次元運動：慢性障害との関連

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Chapter 1 Introduction

1.1 Preface

Overuse injury is a very common problem in sports. The overuse injuries, also called as chronic injury [1-3], is caused by overuse of or repeated impact on one or more parts of the body[4] as the name suggests, for example, the shoulder and elbow injuries in baseball and tennis, shoulder and back injuries in swimming and weightlifting, back injuries in gymnastics and so on[5-11]. Excessive joint motion, as the joint motion beyond physiological range of motion, used repeatedly in sports activities was a proposed etiologic factor for overuse injury[4,11-13]. The excessive joint motion would generate abnormal stress to the structures within and around the joint[14-16]. With such movement repeated thousands times during training and competition of sports, overuse injury might occur as a consequence.

Sports activities are likely to require the joint to move to an excessive configuration, such as excessive shoulder and elbow rotation in the tennis serve and baseball pitching, hyperextension of low back in swimming and gymnastics[12,17]. However, does the excessive joint motion really occur in sports and relate to overuse injuries? From the findings of previous studies, the joint motion in some sports activities which looks excessive for the joint was not as much as the general image from the visually observation[18-20]. For example, shoulder motion in the catch position of weight lifting looks like a shoulder hyperextension; the weight lifter elevated arm to the position much far behind his head (figure 1.1). But the measured results for glenohumeral joint configuration of 10 members from collegiate weight lifting team in the catch position showed that the glenohumeral joint only elevated at 95 ± 6º as a well-known stable glenohumeral configuration named zero position[21]. In baseball pitching, shoulder at a large extent of external rotation was supposed to induce the risk of internal impingement syndrome. The internal impingement was known to occur at excessive glenohumeral external rotation with horizontal abduction angle over 30º [18,22]. However, the previous study[18] examined 51 elite baseball pitchers (contained the members from both collegiate and professional teams) and found no pitcher in the risk of internal impingement at the instant at the arm attaining to the peak external rotation angle during pitching.

In swimming, the excessive joint motions were also supposed to be an etiological factor for the common overuse injuries on shoulder and low back. More than half the competitive swimmers experience some athletic injuries in their career[1,10,23,24] and most of these injuries are classified as overuse injuries[3,10]. These overuse injuries frequently occur at swimmers' shoulders and low back[10,23,25]. Improper shoulder and torso motion, such as arm hyperextension during stretch phase, "high elbow" position in the catch phase, torso hyperextension during swimming, was suggested to generate abnormal stress in the joint and to develop the risk of overuse injury[23,26,27]. Consequently, torso hyperextension and glenohumeral elevation/internal rotation beyond the physiological range were the excessive joint motions proposed to be responsible for low back pain and shoulder pain among swimmers[12,25,26,28,29]. Since swimming is a cyclic locomotion and swimmers perform strokes repeatedly thousands times in training and competitions[23,30], an excessive joint movement, if it occurs at a specific phase of the stroke cycle, causes abnormal stress on the joint repeatedly over thousands times every training sessions. However, both torso and glenohumeral joint performed complicated three-dimensional movements during swimming which were not evaluated accurately from the visually observation. No study determined the three-dimensional movements of torso and glenohumeral joint in swimming. Besides, determining excessive joint motion for a joint with three freedom of rotation is not a simple task, since the physiological range of motion for such joint in one plane may be restrained by the motion in other two planes[31-34]. No evidence, therefore, was provided to evaluate if the excessive joint motion occurs in swimming, when and how it occurs during stroke cycles and the relationship of excessive joint motion to overuse injuries.

This thesis, therefore, was aimed to determine the three-dimensional movements of torso and glenohumeral joint during front crawl swimming and to evaluate if these joint motions exceed the physiological range. The findings were expected to provide firm evidence to discuss implications of joint motions to overuse low back pain and shoulder pain in swimming. If the excessive joint motion occurred during swimming, knowing when and how it occurs during strokes may expect to help to modify the improper technique and avoid injury.

The following hypotheses were tested in this thesis:

1. Swimmer's torso extends beyond the physiological range consistently over multiple stroke cycles during front-crawl swimming, and
2. Swimmers rotate the glenohumeral joint internally and/or elevate the glenohumeral joint beyond the physiological range consistently over multiple stroke cycles during front-crawl swimming.

1.2 Terminologies

(1) Excessive joint motion

In the present study, the excessive joint motion is defined as the joint movement beyond the physiological range of motion. For a joint which has only one degree of freedom, such as the hinge joint, the excessive joint motion can be simply determined as the joint motion beyond the physiological range of motion in the plane of which the joint could move. For a multi-axial joint which moved in more than one plane, the physiological range of motion in one plane could be represented as a unique value as the rotations in other planes are given. Therefore, the physiological range of motion for multi-axial joint is not a simple value but should be expressed as a two-dimensional curve or a three-dimensional surface which indicates a series of the maximal angle for every given angle/combination of angles in other planes. The joint motion exceeded this curve or surface could be considered as the excessive joint motion. The excessive joint motion was assumed to cause the structures in the joint to be subjected to abnormal stress [4,12], predisposing the swimmer to overuse injuries.

(2) Physiological range of motion

The physiological range of motion of a joint is defined as the range of joint motion which permitted by the physiological function as the bone architecture, ligamentous arrangement, muscle extensibility and muscle ability of contraction. Therefore, the physiological range of motion can be achieved by subject's effort of generating muscle forces around the joint. Different as the physiological range of motion, the anatomical range of motion is the range of motion permitted by the anatomical structures, such as bony architecture, ligamentous arrangement and muscle extensibility. Therefore, the anatomical range of motion, generally, should be equaled or larger than the physiological range of motion. The anatomical range of motion would be achieved by the assistance of a large external force applied on the joint rather than the self-effort. This indicates that the joint could be moved to exceed the physiological range of motion due to other external force which could bring the joint abnormal stress and cause micro trauma[15].

In clinical settings, physiological range of motion is measured in the three principle planes independently[35]. This measurement may be problematic for the measurement of ROM of a multi-axial joint because a motion in one plane may be affected by a simultaneous movement in other planes. For example, the physiological range of elevation of the shoulder (glenohumeral) joint in the scapular plane is altered if the internal rotation angle of the elevating arm is changed. Specifically, if the elevating arm is internally rotated to a large extent, the amount of elevation that the arm could reach is substantially reduced. This is believed to be due to the compressive force generated between the coraco-acromial arch of the scapula and the greater tuberosity of humerus, inhibiting one or more of the three rotational degrees of freedom at the shoulder joint. A unique value representing the range of joint motion in each plane should, therefore, be meaningful only if the rotations in other planes are given. In the present study, the physiological range of motion of the multi-axial joint was not represented as a single value for each plane, but it was expressed as a three-dimensional surface data indicating a series of the maximal range of joint motion on one plane for every given combination of joint motions in the other planes.

(3) Stroke phases in front crawl swimming

In the present study, one stroke cycle was divided into two phases, (a) pull phase and (b) recovery phase. The pull phase was farther divided into (a-1) hand entry, (a-2) stretch, (a-3) outsweep, (a-4) insweep and (a-5) upsweep phases. The hand entry phase begins at the instant at which the hand first touches the water and lasts until the arm attaining the peak elevation angle. This phase occupies about 10% of the time spent in one stroke cycle. The hand entry phase is followed by the stretch phase which occupies about 10% of the time spent in one stroke cycle until the hand starting to pull towards outside of the body. The outsweep phase is the next, lasting for about 20% of the time spent in one stroke cycle until the hand starting to move inwards. The insweep phase lasts for about 20% of the time spent in one stroke cycle until the hand starting to move upwards. The upsweep phase lasts for about 10% of the time spent in one stroke cycle until the arm comes out of the water. The recovery phase lasts for about 30% of the time spent in one stroke cycle until the hand entry into the water again.

1.3. Literature review

1.3.1 Incidence of injuries in competitive swimming

Competitive swimming has high prevalence of injury. Wolf et al. [10]reported 67% of

Division I swimmers experienced injuries during a five-year period, and 37% of injuries resulted in missed time of swimming. Abgarov et al., [23]Studied injury history on 170 university-level swimmers, and found that the ratio of swimmers with injury history was 62% and increased to 70% during the competition season. Katayama et al.[3] investigated injuries on 301 elite swimmers who participated in the camp of International championship and found 59% of swimmers attending to the competitions with injury. The incidences of injuries among swimmers were found to be no statistic difference in sex[23]. A greater proportion of injuries were overuse injuries which were reported as two times as acute injuries[1,4,23]. Overuse injury to shoulder, low back and knee are the major complaints among swimmers[3,10]. Shoulder was reported to be the most common injury site among swimmers, with the high prevalence from age 15 to 22 [23]. The prevalence of overuse injuries on the site of body was different among stroke styles[3]. Front-crawl swimmers are most susceptible to the low back pain with followed by shoulder pain. The most common complaint in butterfly swimmers is shoulder pain, followed by low back pain and elbow lesion. The knee injury had the highest occurrence in breaststroke swimmers[36]. The complaints on low back, shoulder and knee are reported almost equally in swimmers specialized in back stroke and individual medley relay[3]. The differences of the injury patterns among swimmers were suggested to be affected by the different body movements in each stroke style[3]. According to these previous studies, the overuse injuries, especially the shoulder pain and low back pain, are severe problem in swimming. To avoid these overuse injuries among swimmers, to clarify the mechanism of overuse injuries occurring in swimming is necessary.

1.3.2 Mechanism of low back pain in swimming

Overuse low back pain is a pain on the low back region with a slow onset and last for long time. The diagnosis on low back of competitive swimmers included the muscle and/or ligament sprains, herniated disc, facet joint injury, spondylolysis and disk degeneration.[14,37-39] The low back pain with muscle and/or ligament strain was supposed to cause by constant forcibly torso extension[40]. Spondylolysis is a defect of pars interarticularis of the vertebra arch caused by repeated torso flex-extension[14,40]. Disc degeneration as a disc lose the water content was suggested to be the consequence of large stress[37,38]. Kaneoka et al.[37] evaluated lumbar disk degeneration with magnetic resonance imaging (MRI) for elite swimmers participated in National training camp and the swimmers from recreational swim club. Their results showed 68% of elite swimmers and 29% recreational swimmers had lumbar disk degeneration. The occurrence of disk degeneration on the L5/S1 was significant higher in the elite swimmers. Hangai et al.[38] also reported a significant high occurrence of disk degeneration in competitive swimmers than non-athletes. Nyska et al[14] examined four elite swimmers who complained of low back pain was diagnosed to have spondylolysis. In a team doctor's report[41], 15% of swimmers in Olympic Games from Japan had low back pain when they were forced to hyperextend the torso and 25% of swimmers complained of low back pain with Kemp's test – a test in torso extension for an intervertebral disc lesion. The occurrence of these low back pathologies among swimmers was suggested to be caused by the repeated large stress from cyclical extension of torso during swimming training[12,14,37,40]. General images from visually observation suggested that to keep in good body alignment during swimming stroke, swimmers hyperextended the lumbar spine and provided large stress to the spine structures[12,14,41]. Besides, training devices, such as fin and beat board during swimming was also suggested to increase the hyperextension of the torso and generated more stress to the lumbar spine[14,41]. Muscle weakness was suggested to induce the low back hyperextension during swimming and proposed to be risk factors of low back pain among swimmers[28,40-42]. A simulation study showed that large stress in the sagittal plane on the lumbar spine during front crawl swimming and the increasing of stiffness for the core muscles decreased the motion range and the stress of lumbar spine in the sagittal plane[43]. Lumbar stabilization exercises that focused on strengthening deep trunk muscles, such as the abdominal “drawing-in” maneuver and a variety of dryland exercises performed in the prone kneeling position, have been found to relieve overuse low back pain among swimmers[40,42]. However, no valid evidence was provided to firm the torso hyperextended in swimming, when and how the hyperextension occurs during swimming was not clear yet.

1.3.3 Mechanism of shoulder pain in swimming

Shoulder pain among swimmer is a pain usually on the anterior and lateral of the shoulder which was caused by the impingement syndrome, supraspinatus tendonitis, labral tear and capsule laxity[30,44,45]. The pain on the anterior and lateral of the shoulder experienced by swimmers was used to be suggested as the consequence of repeated compression of the subacromial structures under the coraco-acromial arch that can occur in the course of normal arm elevation[27,46-48]. The pathology and pain in the anterior part of shoulder was, therefore, named as "subacromial impingement syndrome"[48]. Such mechanical impingement under the acromion was suggested to occur due to (a) a forceful arm elevation beyond the normal range[21,29,49] and (b) arm elevation above shoulder height with the arm rotated internally[29,34,48,50]. The Neer's impingement test and Hawkins impingement test are two postures which induces the pain in the subacromial structures[13,48,51]. In the Neer's test, the examiner passively elevates the patient's shoulder to the maximal elevation with stabilizing the scapula. In the Hawkins test, the examiner stabilized the patient's scapula and passively internal rotates the shoulder of patient to the maximum with the patient's shoulder forward flexion at 90° [52]. Neer and Hawkins tests were suggested to be sensitive to the impingement syndrome, but it is not specific to the structures pathology [51,53].

Recent studies indicate that the mechanical contact of the rotator cuff with acromion was not enough to explain the pathology of rotator cuff injuries in overhead arm positions[53]. Most of evidences on the mechanical contact of structures during glenohumeral joint motion were focused on the Neer and Hawkins impingement postures. The studies used biplane X-ray images with the subject-specific CT bone models to examine the distance between the acromion and humerus during arm abduction. The results showed that the contact of the acromion was not made with the rotator cuff tendon, but it was made with the greater tuberosity of humerus when the arm was elevated above the shoulder height[54,55]. Pappas et al[51] examined the Neer and Hawkins impingement sign by using MRI and found that the acromion did not make contact with the rotator cuff in the Neer's impingement posture but it did in the Hawkins' impingement postures; and a contact of rotator cuff with the glenoid rim was observed in both postures. The rotator cuff passing under the anterior part of acromion was observed in the shoulder configurations with the arm abduction angles below approximately 70°[55,56]. Yamamoto et al[16] measured the contact pressure under the coraco-acromial arch in the cadaveric shoulders in the so-called "modified Neer's postures (Neer posture of humeral elevation with various amount of internal rotation[52] in addition to the Neer's posture). They found that when the arm was elevated above the shoulder height, the contact pressure between the coraco-acromial arch and the rotator cuff increased as the arm internal rotation angle increased. Yanai et al[57] used B-mode ultrasound devise to estimate the pressure under the coraco-acromial arch in the posture of Hawkins impingement test posture, arm abduction at 90°, arm abduction at 90° with the maximal internal rotation and with the maximal external rotation. The pressure under the coraco-acromial arch was significantly higher in the Hawkins posture and the 90° arm abduction with internal rotation than others. These studies indicate that the contact stress on the rotator cuff and coraco-acromial arch occurs in the arm internal rotation rather than the arm elevation with no axial rotation, although the mechanism of contact on the rotator cuff in all shoulder configurations throughout the physiological range of motion have not been examined so far, and thus it is not as yet clear. Besides, the rotator cuff pathology in swimming was suggested to induce the scapular dyskinesis and muscle weakness of the shoulder[28,58]. Muscle weakness of the swimmers shoulder was suggested as a sign of rotator cuff degeneration[28]. Scapular dyskinesis was found to be related with overuse shoulder pain in athletes and increased after swimming training session[45,59]. The scapular dyskinesis was suggested to associate with the risk of internal and subacromial impingement on the glenohumeral joint[45,59,60], but alteration of scapular kinematics was a cause of compensation of the shoulder pathology was not confirmed. According to these studies, the detailed glenohumeral configuration (i.e. the related position and orientation of humerus to scapular) is important information to discuss the mechanism of rotator cuff pathology among swimmers. However, no study determined the glenohumeral joint motion during swimming, whether or not a given glenohumeral joint is configured in a risk inducing position during a given swimming performance, and when and how the swimmer configures the risk inducing glenohumeral joint position in swimming have not been examined.

Figure 1.1— the catch position in the weight lifting (figure by Maruyama, 2012, unpublished thesis)

Chapter 2 Three-dimensional torso motion in tethered front crawl stroke and its implications to low back pain

2.1 Introduction

Low back pain is a common problem among competitive swimmers.[25,28,37] Katayama et al.[3] reported that 46 of 76 International-level swimmers (61%) experienced low back pain in their swimming career and that those swimmers who experienced low back pain were mainly those competing in the front crawl and butterfly events. Wolf et al.[10] assessed a database of injury reports for Division I colleges in the United States and found that 38 of 94 swimmers (40%) had experienced back or neck injury. The injuries described in these reports are only those overuse injuries that occurred as a consequence of swimming-related activity. The studies suggest that 40-60% of elite swimmers experience low back pain and that front crawl and butterfly swimmers are those most susceptible to low back pain.

Epidemiological studies identified three major factors associated with low back pain among swimmers: muscle weakness,[28,61] overtraining[2,37] and repeated torso hyperextension.[12,25,28] Lumbar stabilization exercises that focused on strengthening deep trunk muscles, such as the abdominal “drawing-in” maneuver and a variety of dryland exercises performed in the prone kneeling position, have been found to relieve overuse low back pain among swimmers.[12,28,42] Goldstein[62] used a magnetic resonance imaging technique to examine spinal abnormalities (disk degeneration or spondylolysis) in 19 female competitive swimmers and found that those participants who demonstrated spine abnormalities had more hours of training per week than those without such abnormalities. Kaneoka et al.[37] used a magnetic resonance imaging technique to examine abnormality of the lumbar spine in 56 swimmers who participated in Japanese national training camps. Their analysis revealed that disk degeneration was present in 68% of the swimmers and prevalence was highest in front crawl swimmers. They also found that the prevalence of lumbar disk degeneration was significantly higher in elite competitive swimmers than recreational swimmers and suggested that overtraining, such as excessive swimming distance and/or training duration, might exacerbate lumbar disk degeneration. Swimmers who complained of low back pain were often diagnosed as having spondylolysis of the lumbar vertebrae.[14] Spondylolysis or disk degeneration of the lumbar spine is generally caused by repeated mechanical stress on the spine. One factor for spondylolysis is repeated hyperextension.[14,62] The hyperextension of torso required in swimming—such as repeated torso hyperextension in breaststroke and butterfly and repeated hyperextension with twist and/or lateral tilt during front crawl and backstroke —is a commonly claimed etiology of low back pain among swimmers.[12,28]

Among the common etiological factors identified to explain the cause of low back pain in swimmers, repeated torso hyperextension is directly related to the kinematics of swimming. In swimming, swimmers exhibit twisting and lateral bending of the torso in addition to torso extension; thus, evaluation of torso hyperextension requires a detailed analysis of complex three-dimensional torso configurations rather than simple analysis of sagittal plane motion. Studies have suggested that complex and excessive three-dimensional joint motions in sports activities are related to low back pain, such as excessive low back extension in gymnastics,[63] torso hyperextension with lateral tilt in tennis[64] and torso hyperextension with twist in cricket bowling.[65] However, to our knowledge, no biomechanical study has quantified three-dimensional torso configurations in swimming and discussed the implications for low back pain. The purpose of this study, therefore, was to describe the three-dimensional configurations of the torso in the front crawl and to test the hypothesis that swimmers experience torso hyperextension consistently across stroke cycles.

2.2 Methods

In this study, torso hyperextension was considered to be extension beyond the physiological range of torso extension for a given amount of torso twist and lateral tilting. Generally, hyperextension of a joint is defined as joint extension beyond the physiological range of motion.[66] However, because the full extent of torso extension is reduced by simultaneous motion in other planes,[32,33,67,68] the physiological range of torso extension should not be considered to be a unique value, but should rather consist of the maximum extension angle for every given combination of torso twist angle and lateral tilt angle. We determined a series of maximum torso extension angles for every combination of twist and lateral tilt angle throughout the functional range, and used it as a baseline to judge if the torso at a given instant during swimming is hyperextended. We named this series of maximum torso extension angles, determined for each participant, as the participant's "three-dimensional range of torso motion (3D-ROM)".

Experiments were conducted in an indoor swimming pool (size 50 × 25 m; depth

1.3–4.0 m). Nineteen members of a men's collegiate swimming team participated in this study (body height: 1.75 ± 0.04 m; body mass: 68.9 ± 4.0 kg; age: 20 ± 1.3 y; training career: 13 ± 3.4 y). Each participant was asked to fill out a questionnaire on their injury history. No participant complained of low back pain or any other injuries that affected their performance on the day of this experiment. This study was approved by the institutional committee of research ethics and all participants provided written informed consent before participating.

A simplified kinematic model consisting of a thorax and a pelvis was used to describe the torso configurations. An electromagnetic tracking device (LIBERTY, POLHEMUS, VT, USA) consisting of a control unit, transmitter, stylus, and sensors was used to record the movements of the two segments at 240 Hz. The transmitter generated a hemispherical magnetic field, defining the global coordinate system, and each sensor measured its position and orientation relative to this system. The stylus was a pen-shaped tool used to measure three-dimensional coordinates of a given point in the global coordinate system. The operation range of the magnetic field generated by the transmitter was within a hemisphere with radius 2.10 m, and the static accuracy within the operation range, described as the root-mean-square value of the measurement errors (RMSE), was reported to be 0.76 mm for position and 0.15° for orientation according to the factory specification manual.

Electromagnetic tracking devices have been widely used for measurements of body segments' movement in clinical and sports settings on dry land,[20,69,70] but have not been used in underwater conditions. The experimental environment, comprising such elements as the water and the metal frames behind the walls of the swimming pool, was expected to distort the magnetic field. The experimental set-up for data collection was carefully arranged so as to minimize the measurement error due to this magnetic distortion. The transmitter was attached to one end of a 2-m-long fiberglass pole horizontally extended from the lateral side of the swimming pool, where it was firmly fixed onto the elevated section of the pool deck (Figure 2.1). With this arrangement, the transmitter was positioned 1.7 m from the lateral side of the pool, 2.5 m from the frontal side of the pool and 0.35 m above the water surface. The valid test section for the measurement of torso motion around the transmitter above and below the water surface was identified using a 0.6 m calibration bar to which two sensors were attached at a known distance apart and relative orientation. When the calibration bar was moved throughout the operation range, the measurement error was determined in real time as the variation from the known position and orientation of one sensor relative to the other. By limiting the allowable measurement error to within 10 mm for position and 3° for orientation, the size and shape of an appropriate measurement field around the transmitter was determined to be a hemisphere with a radius of 0.9 m.

The sensors were waterproofed (STELLA Precision Co. Ltd., Japan) and attached to a participant's mid-sternum and central sacrum, using double-sided tape and elastic medical tape to attach the sensors to the skin. These sites were chosen as they lack muscle tissue between the bone and skin. To define the position and orientation of the thorax and pelvis relative to the corresponding sensor, seven body landmarks were palpated and digitized by an experienced operator using the stylus (Figure 2.2). The suprasternal notch (SN), the processus xiphoideus (PX), the processus spinosus of the 7th cervical vertebra (C7), and the processus spinosus of the 8th thoracic vertebra (T8) were used to define the thorax-embedded reference system. The symphysis pubis (SP) and the left and right anterior superior iliac spine (L- ASIS, R- ASIS) were used to define the pelvis-embedded reference system. A local reference system was defined for each segment as follows: For the thorax-embedded reference system, the long-axis (*Tz*) was defined as the unit vector pointing from the midpoint between PX and T8 to the midpoint between SN and C7. The transverse axis (*Tx*) was defined as a unit vector perpendicular to the plane defined by C7, SN, and the midpoint between PX and T8, pointing toward the right side of the body. The sagittal axis (*Ty*) was the cross product of *Tz* and *Tx*. For the pelvis-embedded reference system, the long-axis (*Pz*) was defined as the unit vector pointing from SP to the midpoint between L-ASIS and R- ASIS. The sagittal axis of the pelvis (*Py*) was defined as the unit vector perpendicular to the plane defined by L- ASIS, R- ASIS, and SP, pointing forward. The transverse axis (*Px*) was the cross product of *Pz* and *Py*. Assuming that each of these local reference systems did not change its position and orientation with respect to the sensor attached to the corresponding segment, the orientation of the segment at any given instant during the body movement could be determined in the global coordinate system. The torso configuration at every given instant was determined as the orientation of the thorax relative to the pelvis, expressed as three sequential Cardan angles: extension angle, lateral tilt angle, and left/right twist angle.

Measurements were taken shortly after a 1-h team practice session. After a rest period and a 15-min warm-up session (light swimming with self-chosen style and speed, and a normal stretching period), each participant underwent two data-collection sessions, comprising a 3D-ROM measurement and a measurement of torso configurations in front crawl swimming. The warm-up routine was not interrupted until the participant felt they were ready for the measurements, at the same physical condition as in a normal team practice session. All measurements were taken in the section of the swimming pool with water depth 1.30 m. During 3D-ROM measurement, the participant was asked to submerge himself in the water in a supine position with the help of an examiner, who stood on the pool floor and stabilized the participant's pelvis manually with both hands. Nose clips were provided for the participants. The participant was then asked to perform a complete arc of torso extensions in the water at a series of twist angles, while his torso was maximally tilted laterally (Figure 2.3). With this arrangement, the gravity of the participant's body was counter-acted by its buoyancy, minimizing the muscular effort required to measure the physiological range of extension. The twist angles were set at approximately every 10° interval from no-twist to the maximum twist angle. The twist and lateral tilt were performed towards the preferred breathing side and the 3D-ROM for the non-breathing side was assumed to be symmetric to the breathing side. The 3D-ROM was determined from the sections of each arc of complete extension. The series of extension angles extracted from all arcs of extension for each participant were expressed as a function of lateral tilt and twist angles to determine the 3D-ROM for each participant (Figure 2.4). Test-retest reliability for the determined torso 3D-ROM was assessed. Six participants were asked to perform the complete arc of torso extensions using the same process as in the 3D-ROM measurement (up to 10 trials per subject), with the twist angle for each extension specified by the tester. The maximum extension angles determined from these trials were compared with the corresponding values determined from the individual's 3D-ROM and the RMSE was determined. The mean value of the RMSE across the 6 participants was 2.5 ± 2.1° with a coefficient of variance of 4.7 ± 4.1%.

In the front crawl measurement session, each participant performed tethered swimming (Figure 2.1). The participant was restrained by rubber tube and was asked to swim at their maximum effort used in normal training for a sprint race, and to breathe every 2 stroke cycles. The average stroke time in the present study was 1.27 ± 0.12 s. This stroke time falls within the range of male world-class swimmers for 200 m freestyle (1.17–1.39 s) according to previous studies[71,72]. This indicates that the observed stroke time is a typical stroke time for a mid-distance event with maximal effort. The participant was restrained by a rubber tube; this equipment was used frequently in daily training and was familiar to the participant. One end of the rubber tube was connected to a belt that was fastened around the swimmer's waist and the other end of the tube was held by an examiner. The examiner carefully adjusted the length and tension of the rubber tube during the first 2-3 stroke cycles so that the participant was kept within the test section under constant tension for the remainder of the stroke cycles. With this arrangement, the participant was allowed to swim with a slight backwards and forwards rhythmic motion during the measurement due to the elasticity of the tube. The angle of the rubber tube was maintained at approximately 7° from the horizontal. The participants practiced several trials until they were familiar with the procedure. Then, each participant performed between 12 and 17 stroke cycles. The first 3 stroke cycles were used for the examiner to adjust the length and tension of the rubber tube to position the participant at the center of the test section. Our participants were highly reliable in performing the tethered swimming experiment. The mean value across participants for the variation of the largest extension angle exhibited in the stroke cycles without breath action (4 stroke cycles per person) and in the stroke cycles with breath action (3 stroke cycles per person) were 2.2° and 1.7°, respectively. The coefficient of variation for the stroke time was analyzed across seven stroke cycles and was found to be 4.4% on average.

The torso extension angle observed at every given instant from the fifth to eleventh stroke cycles (4 stroke cycles with breathing action and 3 without) during front crawl swimming was compared with the individual 3D-ROM. If the torso extension angle exhibited at a given instant was equal to or exceeded the 3D-ROM, the torso at that instant was judged to be hyperextended. The results of the torso kinematics during the fifth to eleventh stroke cycles were calculated as means and standard deviations. If the participant exhibits the torso hyperextension in every stroke cycles during the fifth to eleventh stroke cycles, the participant was judged to be consistently hyperextending the torso. A paired *t* test was used to determine whether the torso configuration was different between the stroke cycle with and without the breathing action. Statistical significance was set as $P < .05$.

The validity of the method used for the measurement of torso extension angle was assessed as follows: The first test was conducted to determine which section of the spinal motion was represented by the torso extension angle determined using the present method. A participant was asked to pause in three configurations—a standing position, maximally flexed position, and maximally extended position—within the field of view using X-ray photography. The configurations of the axial skeleton in the sagittal plane were recorded with X-ray photography and the torso extension angle was simultaneously measured with the electromagnetic tracking device. The inclination angle of the superior surface of each vertebra from T5 to L5 was measured manually on the X-ray images, and expressed as the angle relative to the pelvis (Table 2.1). Among the inclination angles of the 13 vertebrae, the angle of T9 relative to the pelvis was found to best match the torso extension angles measured with the electromagnetic tracking device (the mean difference between the two sets of angles across the three positions was 3°, Figure 2.5). This result indicates that the torso extension angle determined with the present method represents the sum of the angular displacements of the lumbar spine and the lower section of thoracic spine relative to the pelvis.

Another test was conducted to compare the present method with a widely used tape measurement method[73,74] to determine the validity in measuring the extent of lumbar extension over a large range. Two bony landmarks (the intersection of the line along the spine and the line passing through the left and right posterior superior iliac spine, and 15 cm superior to the first marker along the line of the spine) were selected for the measurements. Using the tape measurement method and the present method, the extent of lumbar extension was measured simultaneously for 4 participants in four body positions each; the standing position and three levels of torso extension in the quadruped position. The tape measurements were significantly correlated with the torso extension angle determined with the present method (Pearson's r ranged from -0.955 to -0.981 for each participant; Figure 2.6), indicating that the torso extension angle determined with the present method is well associated with the extent of the extension of lumbar spine over a large range. The results of the two tests suggest that the torso extension angle determined with the present method accurately represents the sum of the angular displacement of the low back over a large range.

2.3 Results

The torso extension was observed over a large range of twist and lateral tilt angle during front crawl swimming (Table 2.2, Figure 2.7). No significant difference was found in these angles between the stroke cycle with and without breathing ($P = .963$ for extension, $P = .138$ for tilt and $P = .814$ for twist). The largest torso extension angle within each stroke cycle was recorded at or around (0.02 ± 0.08 s), the instant that the torso attained the largest twist angle (29 ± 8°). At the instant at which the torso extended to the largest extent in each stroke cycle, the torso twist and lateral tilt angles reached 20 ± 11° and 7 ± 6°, respectively.

No participant exhibited torso hyperextension consistently across the strokes during the swimming measurement. The torso extension angles during the front crawl swimming were much smaller than the corresponding 3D-ROM for all participants except one. The mean value across participants for the minimum difference between the extension angles during swimming and the individual 3D-ROM was 22 ± 11° (from -1° to 39°). At the instant that the minimum difference was observed, the extension angle, the lateral tilt angle, and the twist angle were 11 ± 11°, 11 ± 9°, and 20 ± 12°, respectively. One participant exceeded his 3D-ROM by 1° for a short period in 1 of the 7 stroke cycles analyzed. This participant attained 19° torso extension angle with 11° left tilt and 34° left twist during the insweep phase of the right arm. This torso hyperextension was observed around the instant at which the largest extension angle was observed in the stroke cycle with breathing and lasted for 0.02 s (2% of the time spent in this stroke cycle).

2.4 Discussion

This study aimed to describe the three-dimensional torso motion in front crawl and to test the hypothesis that swimmers experience torso hyperextension consistently across the stroke cycles. The main findings of the study are that (a) the largest torso extension angle observed during front crawl swimming was 9° on average and it was recorded at or around the instant at which the torso attained the largest twist angle, (b) the torso extension angles were much smaller (by 22° on average) than the corresponding 3D-ROM, and (c) no participant hyperextended their torso consistently across the stroke cycles analyzed. Therefore, our hypothesis was rejected.

The present study demonstrated that the torso extended during front crawl swimming and its peak value was attained while the torso was twisted to a large extent. However, the extent of torso movement during the stroke cycles was not extreme and no subject exhibited torso hyperextension consistently across the stroke cycles. If repeated hyperextension is the primary reason for low back pain among swimmers, the number of participants who hyperextended their torso consistently across stroke cycles should be as high as the incidence of low back pain. Epidemiological studies reported that 40–60% of competitive swimmers had a history of low back pain[3,10,28,37] and 47% of our participants reported a history, yet no participant exhibited torso hyperextension consistently. Moreover, the precise instance of torso hyperextension was observed for only 1 of our 19 participants

(5.3%) in 1 of the 7 stroke cycles. Except for 1 participant, the largest torso extension exhibited during the strokes was substantially smaller than the individual physiological range of motion in all participants. The probability of our participants exceeding their 3D-ROM was 0.8% on average. For the participant who exhibited torso hyperextension in one of the strokes, this probability was 14.6%; for the others it was less than 0.1%. These results indicate that torso hyperextension may occur only once every 1000 stroke cycles for most participants. Therefore, consistent torso hyperextension should be a rare case for a swimmer performing front crawl stroke with maximal effort at a middle distance pace, although this result should be re-examined for non-tethered swimming and fatigued swimming in future studies. Because the participants in the present study were swimmers without low back pain at the time of the measurement, we might have failed to observe improper torso motions that could cause low back pain. It is hard, however, to imagine that a swimmer could perform front crawl strokes with a repeated extreme torso extension beyond their physiological range. More than 22° of additional torso extension is required for our typical participant to hyperextend the torso during the strokes. This large increase in the torso extension angle substantially alters the body's longitudinal alignment and causes the long axis of the body to bend backward severely (Figure 2.7). Front crawl swimming with such a body alignment is rarely seen among competitive swimmers. We believe that torso hyperextension in front crawl swimming, if it occurs, should be a result of decreased physiological range of motion, rather than an improper swimming technique with an abnormally large torso extension. This is to say, torso hyperextension in swimming might be a consequence of the dysfunction of the spine with the reduced physiological range of motion, but not the primary cause of the low back pain. Repeated torso hyperextension beyond the physiological range, therefore, should not be claimed to be the primary mechanism to explain low back pain among swimmers.

There is a possibility that the spinal motion beyond the physiologically available range is not always required to cause low back pain in swimming. Panjabi[75,76] proposed that the neutral zone, reported to be 39.5% of the entire anatomical range of lumbar spine extension,[77,78] may be the critical boundary for developing low back pain, and that the spine when forcibly moved beyond the neutral zone may develop a significant internal force causing the ligaments around the spinal column to stretch.[76] We applied this ratio to our data of range of motion so as to speculate if our participants moved their spines beyond the neutral zone. The result revealed that 8 participants (42% of participants) extended the torso during front crawl beyond the upper limited of individual's neutral zone in one or more stroke cycles (Figure 2.8), including 3 (16% of participants) who extended the torso beyond the neutral zone in all stroke cycles. In addition, a Chi-square test was conducted to determine if the participants with a history of low back pain were independent from those participants who exhibited torso extension beyond the upper limited of neutral zone during front crawl swimming. The result showed that the two variables were significantly interdependent ($\chi^2 = 4.232$, $P = .040$), indicating that those who exceeded the upper limited of neutral zone in front crawl swimming were more likely to have a history of low back pain. We suggest that the excessive joint motion of the spine that causes low back pain in front crawl swimming may be the repeated spinal joint motion beyond the upper limited neutral zone. Future investigation is needed to explore this notion.

Limitations are discussed. Firstly, the 3D-ROM of each participant was assumed to be laterally symmetric and the range of motion in the non-breathing side was not measured. The record of medical/physical checks conducted annually on the swimming team members (including all participants of the present study) showed that the mean value across participants for the maximal right and left torso lateral tilt angles are 44 ± 8° and 45 ± 7°, respectively. The mean of maximal right and left torso twist angles are 50 ± 6° and 52 ± 7°, respectively. These results suggested that our participants are in good balance for the normal torso physiological range of motion. In additional, we examined the lateral symmetry of the 3D-ROM of a healthy male student (body height: 1.70 m; body mass: 59.0 kg; age: 23 y; swimming career: 9 y) and found that the root-mean-square value of the difference between the breathing and non-breathing sides was 5°. This difference was smaller than the mean difference between the 3D-ROM and the torso extension in swimming. The assumption of lateral symmetry in 3D-ROM, therefore, should not affect the main findings of the present study. Secondly, the torso motion during front crawl swimming was collected in tethered- swimming and the findings of the present study may not be directly applicable to the normal untethered swimming seen in free-swimming. Tethered swimming is a widely used training method focusing on increasing the muscle strength of the upper limbs.[79] In comparison with free swimming, swimming with resistance was observed to have a decreased stroke rate and stroke length, as well as an alteration in the ratio of phase durations,[80,81] although no evidence indicated difference in the magnitude of torso movement between the tethered front crawl swimming and free front crawl swimming. Future work should examine whether swimmers experience torso hyperextension during front crawl in free-swimming conditions. Thirdly, the study determined the movement of the sum of lower thoracic spine and lumber spine, no attempt was made to examine the relative movement between each spine vertebra. The joint motion between two specific vertebrae may be excessive and related to low back pain. However, to our knowledge, no valid method could be applied to measure the relative vertebrae motion during swimming. The detail motion of specific vertebra may be the future task for determine the mechanism of low back pain among swimmers.

The findings of this study support the following conclusions:

(1) In tethered front crawl swimming performed by collegiate male swimmers, the peak value of torso extension angle (9 ± 11°) was attained when the torso was twisted to a large extent (20 ± 11°).

(2) Even with the large torso twist angle, the combination of the large twist and extension angles were much smaller (by more than 22°, on average) than the corresponding 3D-ROM. No participant hyperextended the torso consistently in tethered front crawl swimming, rejecting our hypothesis.

(3) Torso hyperextension should not be claimed to be the major cause of the high incidence of low back pain seen among swimmers. Repeated torso motion beyond a specific section of the physiological range of motion (e.g. the individual neutral zone), rather than the whole range of motion, may increase the risk of low back pain in front crawl swimming.

Tables

Table 2.1 The inclination angle of each vertebra relative to the pelvis and the torso extension angles determined with the present method (unit: degree; Positive indicates backward inclination)

X-ray method	Inclination angle of each vertebra relative to the pelvis		
	Neutral	Flexion	Extension
L5	-15	-21	-8
L4	-3	-17	9
L3	7	-14	22
L2	6	-11	28
L1	4	-10	31
T12	-1	-12	28
T11	-4	-16	24
T10	-5	-14	23
T9	-9	-13	21
T8	-14	-15	16
T7	-18	-21	10
T6	-21	-23	6
T5	-21	-23	4

Table 2.2 The mean value across participants for the peak values of three-dimensional torso motion during the stroke cycles with and without breathing action (Unit: degree)

Stroke cycles	The largest torso extension angle (SD)	Left-to-right torso twist (SD)	Left-to-right torso lateral tilt (SD)
With breathing action	9 (11)	54 (12)	36 (7)
Without breathing action	9 (11)	53 (11)	38 (6)

Figures

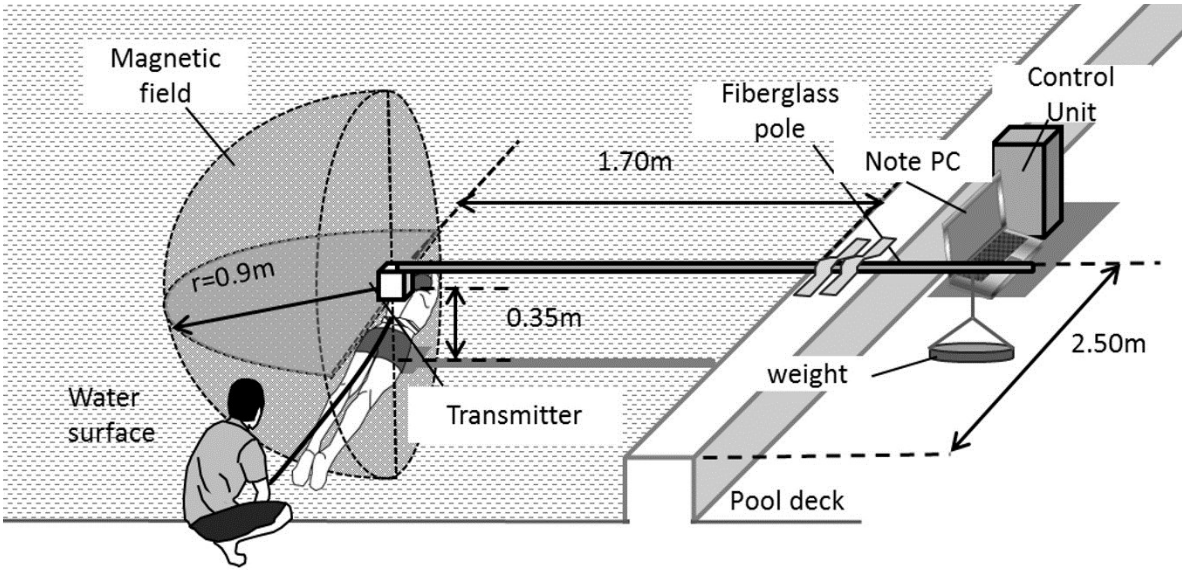

Figure 2.1 — Experimental set up.

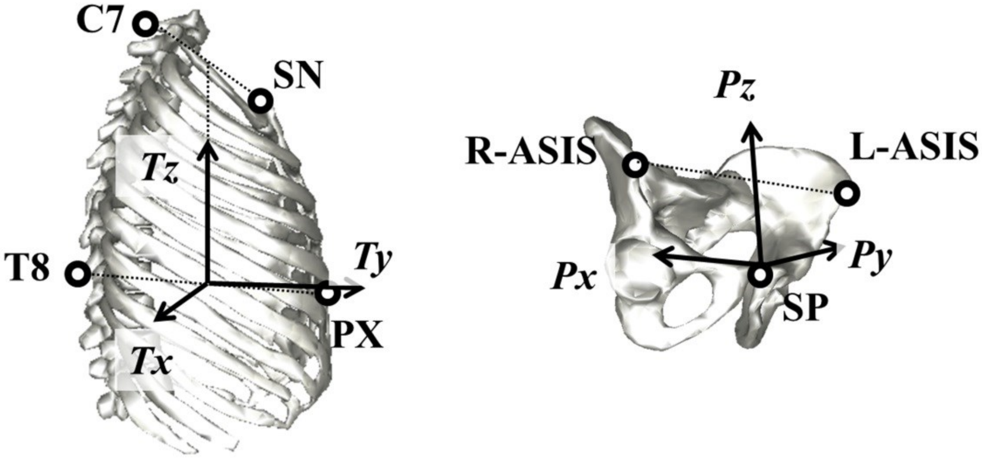

Figure 2.2 — Body landmarks for determining the local reference system.

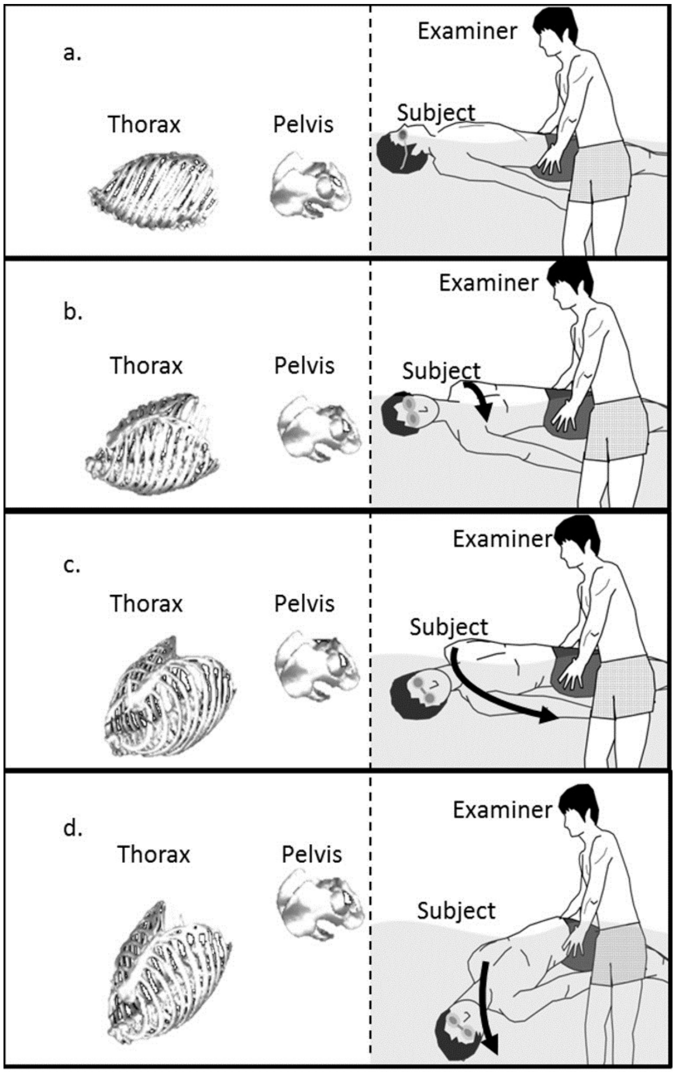

Figure 2.3 — The procedure for 3D-ROM measurement.

(a) Start position: The participant is in a neutral position with no torso extension, twist and lateral tilt consciously. (b) Twist angle is set: The participant twists the torso to the specified extent without extending and laterally tilting the torso. (c) Tilting the torso maximally: Keeping the amount of twist, the participant tilts torso laterally to the maximum extent without extending the torso. (d) Extending the torso maximally: The participant extends torso completely while maintaining the extent of twist and the maximal tilt.

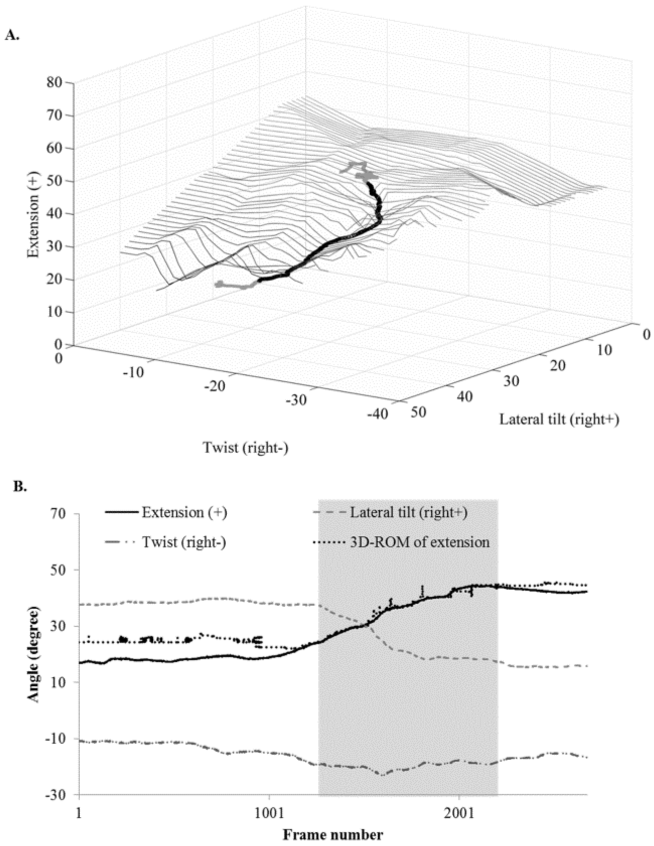

Figure 2.4 — A typical example of an individual’s 3D-ROM.

The three-dimensional surface plotted on the graph A indicates the boundary of the anatomically permissible torso range of motion of an individual (Below the surface is anatomically permissible range and above the surface is not anatomically permissible). The thick-black-gray-line in A indicates a trail of the torso configurations exhibited during one trial of complete torso extension with a given twist angle while the torso was maximally tilted laterally. B shows the time series data of three Cardan angles exhibited in the same trial. The black part of the thick-black-gray-line in A corresponds to the gray vertical band in B, comprising a line section of the surface indicative of the boundary.

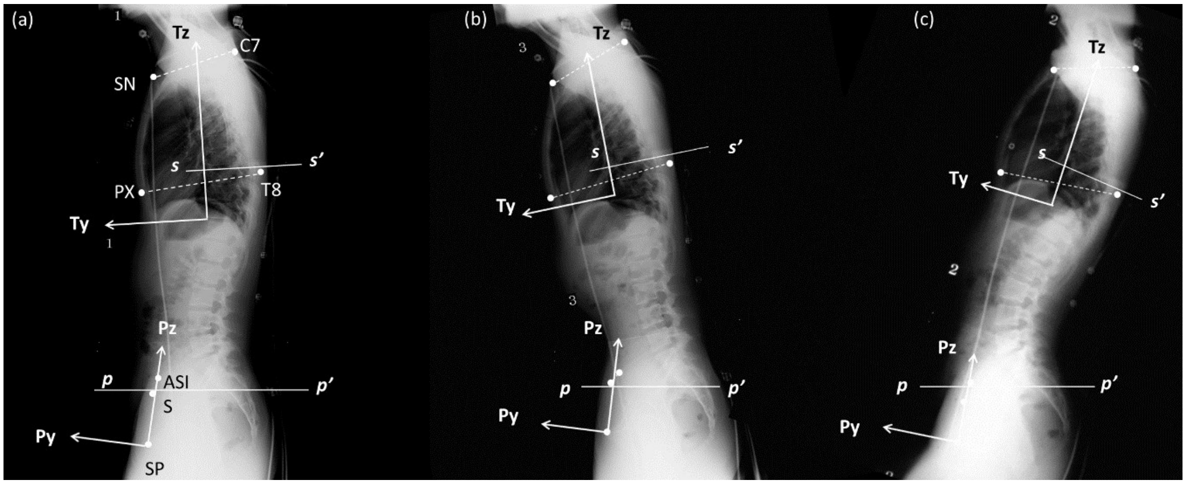

Figure 2.5 — The X-ray photographs used for the validity test (from the viewpoint of fixed pelvis).

(a) a normal standing position (neutral position), (b) the largest flexion and (c) the largest extension of torso within the field of view of the X-ray photography. The torso extension angles measured with the present method were -9º, -14º and 12º for (a), (b) and (c), respectively. The angle between line ss’ and line pp’ indicates the inclination angle of T9 relative to pelvis (-9º, -13º and 21º for (a), (b) and (c), respectively).

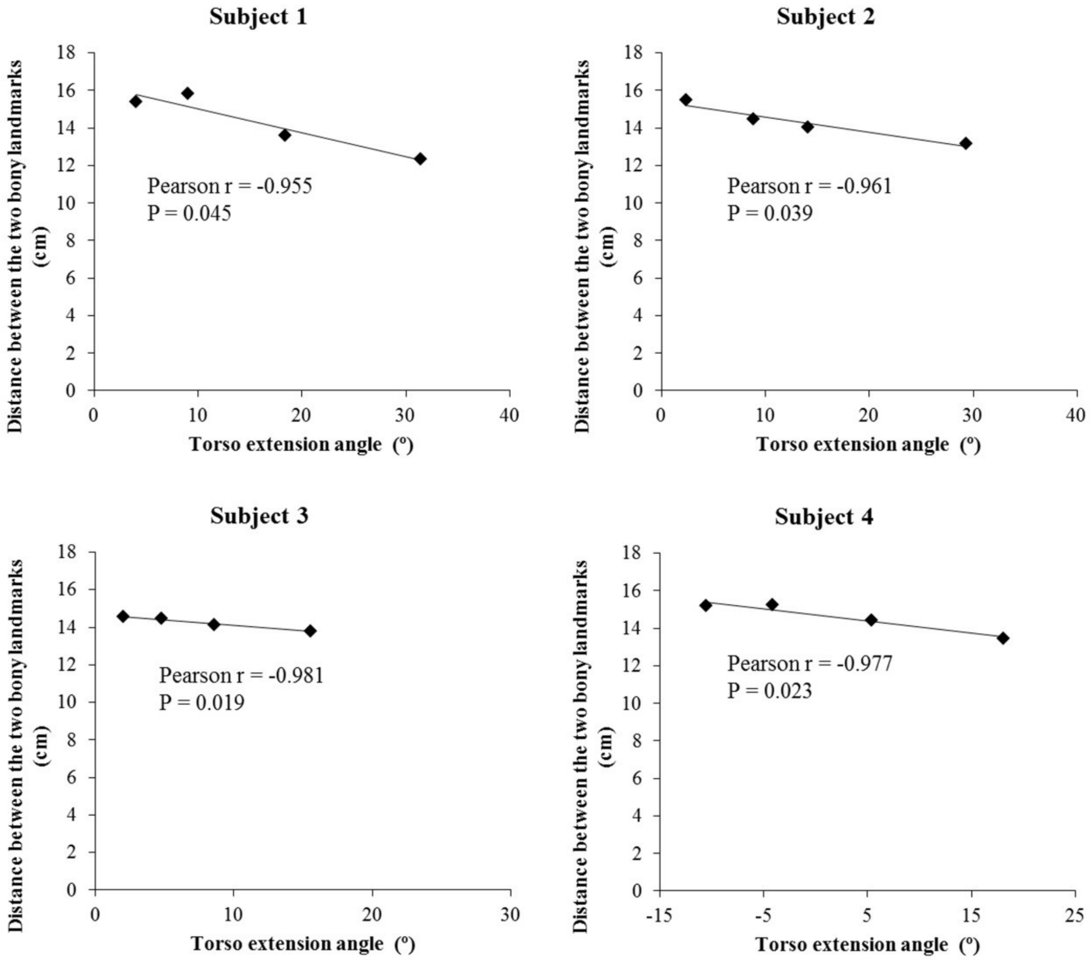

Figure 2.6 — Correlation for the distance between the two bony landmarks (tape measurement method) and the torso extension angle determined with the present method for each participant.

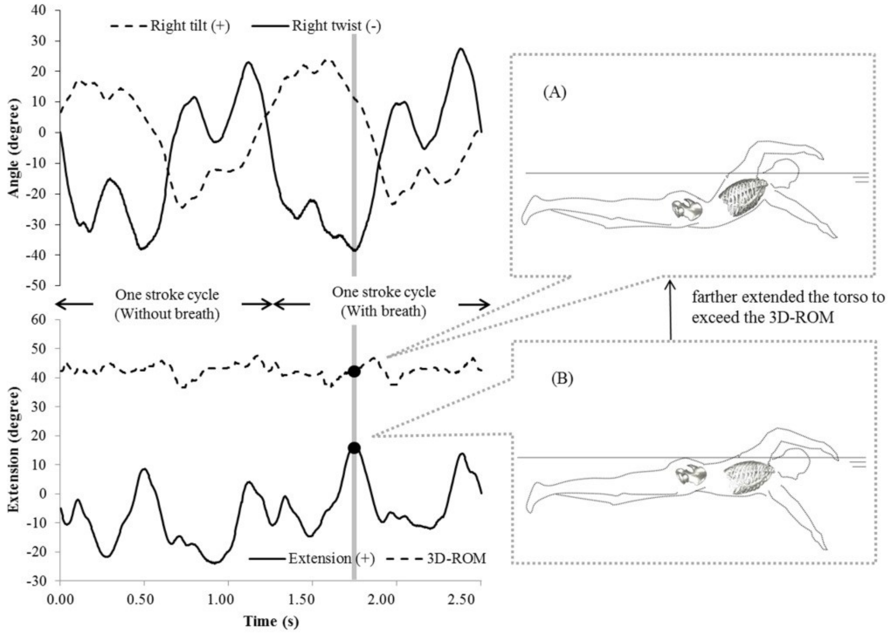

Figure 2.7 — Torso configuration and the corresponding 3D-ROM during front crawl (A typical example).

In this participant, the minimal difference between the 3D-ROM (25º) and the extension angle observed in the strokes was attained in the stroke with breathing. At this instant, the largest extension angle (17º) and the largest twist angle (39º towards the breathing side) were attained simultaneously (at t = 0.53 s, from the instant of torso starting to twist during the stroke cycle with breathing action). The thick gray vertical line indicates the instant at which the largest torso extension angle was recorded. The image (A) illustrates the participant as if he farther extended the torso to exceed the 3D-ROM. The image (B) illustrates the torso configuration of the participant observed in the actual swimming.

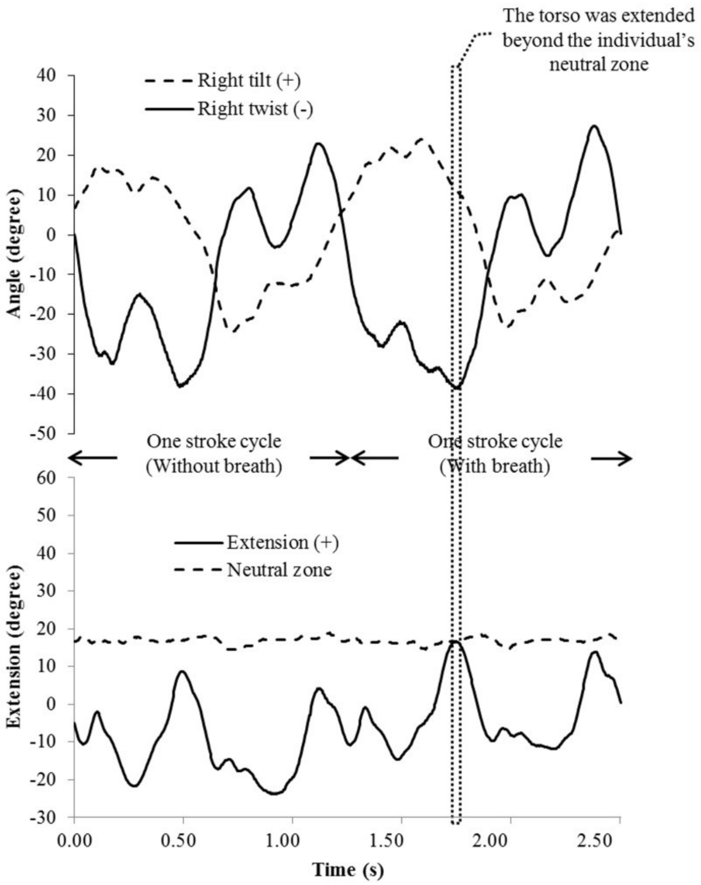

Figure 2.8 — Torso motion and the corresponding individual's neutral zone (A typical example).

Chapter 3 Three-dimensional glenohumeral motion in tethered front crawl stroke and its implications to shoulder pain

3.1 Introduction

Shoulder pain is the most common problem in competitive swimming with an estimated prevalence ranging from 30% to 70% over a typical career[1,27,47]. Abgarov et al.[23] used a questionnaire to evaluate swimming-related injuries in 170 collegiate swimmers participating in a championship event and found that overuse shoulder pain was the most common injury and that the number of complaints increased after the competitive season. Wolf et al.[10] studied the injury patterns of 94 collegiate swimmers on Division I teams in the United States and found that one third of injury cases (55 of 166) involved shoulder pain, with front-crawl swimmers the most susceptible group. The clinical diagnosis of the swimmer's shoulder conditions was usually the impingement syndrome, supraspinatus tendonitis, labral tear and capsule laxity[30,44].

Until recently, the shoulder pain experienced by swimmers was believed to be the consequence of repeated compression of the subacromial structures under the coraco-acromial arch that can occur in the course of normal arm elevation[12,27,46,48,82]. The mechanical contact between the acromion and rotator cuff was confirmed to occur in the so called Hawkins test position; that is, arm forward elevation of 90° with internal rotation[51,83] and the contact pressure between coraco-acromial arch and rotator cuff was reported to increase as the arm elevated at or over the shoulder height was rotated internally[16,57]. The findings of these studies provided convincing evidence to support the belief. However, as the understanding of scapula and glenohumeral joint kinematics advanced, the mechanical compression of subacromial structures between the greater tuberosity of humerus and the coraco-acromial arch was not suggested to be the only mechanism to explain the rotator cuff pathology[55,84-87]. Recent studies showed that the bone-to-bone contact of acromion and humerus, rather than the compression of subacromial structures between the greater tuberosity of humerus and acromion, occurred during arm abduction over shoulder height [54,55]. The mechanical contact between the acromion and rotator cuff was not observed in the so called Neer's impingement test position; that is, the maximal arm frontal elevation with stabilized scapula. Besides, mechanical contact of the articular surface of rotator cuff between the glenoid and humeral head, often called internal impingement, was observed at the Neer's test position and the Hawkins test position[51]. These findings have raised a serious question to the long-held belief[53,55], having jeopardized the former interpretations of the accumulated knowledge about the mechanism of the shoulder pain of swimmers. Although the mechanism of rotator cuff pathology and shoulder pain has not been fully understood, it seems reasonable to suggest that the glenohumeral joint excessive elevation and/or internal rotation is a critical configuration that may generate abnormal stress to some structures of the glenohumeral joint.

Competitive swimming, as an overhead sports, requires arm overhead rotation repeated thousands times during the training program[30,88,89]. Any small trauma developed at any phase of the stroke cycle would be repeated many times over the course of training program, predisposing the swimmer to develop shoulder pain. However, no study has been conducted to examine the kinematics of the scapula and humerus directly during swimming and to determine if any excessive glenohumeral joint motion occurs in swimming. The aims of this study, therefore, were to (a) describe glenohumeral motion, (b) to test a hypothesis that glenohumeral joint exceeds the physiologically permissible range of elevation and/or internal rotation during front crawl stroke cycle.

3.2 Methods

The glenohumeral joint with excessive elevation and/or internal rotation is a critical configuration that may generate abnormal stress to some structures of the glenohumeral joint. The present study aimed to identify these shoulder configurations in the front-crawl stroke. The critical configurations were identified during swimming in two steps. First, glenohumeral configurations known to develop the risk of contact between structures were measured for each shoulder in a controlled setting. In particular, a series of maximum internal rotation angles of the glenohumeral joint were measured for every given combination of horizontal adduction and elevation angles throughout the functional range of the glenohumeral joint to define the critical range of motion (c-ROM) for each individual. In the second step, glenohumeral configurations observed during front-crawl swimming that exceeded the c-ROM (defined as excessive glenohumeral joint motion) were identified as potentially harmful due to the contact on structures of glenohumeral joint. The excessive glenohumeral joint motion beyond c-ROM contains two explanations (a) the glenohumeral configuration exceeded the physiologically permissible range of elevation, and/or (b) the glenohumeral configuration exceeded the physiologically permissible range of internal rotation during front crawl stroke cycle.

Seventeen members of a men’s collegiate swimming team participated in this study (body height: 1.75 ± 0.04 m; body mass: 68.9 ± 4 kg; age: 20 ± 1.2 yr; training career: 14 ± 3.6 yr). No subject had perceivable shoulder pain or any other injuries that disturbed their performance. The study was approved by the institutional committee of research ethics and all subjects provided written informed consent.

Since previous studies[27] reported that the shoulder pain was common in the dominant side of swimmers than on the non-dominant side and all our subjects preferred the right side as their dominant side, only motion of the right shoulder was measured. A simplified kinematic model consisting of the right scapula, right humerus, and thorax was used to describe the configurations of the shoulder complex. An electromagnetic tracking device (LIBERTY, Polhemus, Colchester, VT) was used to record the movements of the three segments at 240 Hz. The spec of the electromagnetic tracking device was same as what used in the Chapter 2 method session.

Three sensors that were professionally waterproofed (STELLA Precision Co. Ltd., Ushiku, Japan), were attached to the skin over the sternum, the flat area of the right acromion, and a plastic cuff wrapped around the right humerus. Double-sided tape and elastic medical tape were used to fix the sensors to the skin. To define the local reference system for each segment, nine body landmarks were palpated and digitized using a stylus (a pen-shaped tool to measure three-dimensional coordinates of each point in the global coordinate system) by an experienced tester. The suprasternal notch (SN), processus xiphoideus (PX), processes spinosus of the seventh cervical vertebra (C7), and the eighth thoracic vertebra (T8) were used to define the thorax-embedded reference system. The acromial angle (AA), root of scapular spine (SP), and inferior angle of scapula (IA) were used to define the scapular-embedded reference system. The medial epicondyle (ME), the lateral epicondyle (LE), and the center of the humeral head (HH) were used to define the humeral-embedded reference system. Assuming that the HH coincides with the glenohumeral joint center, the position of HH with respect to the sensor attached to the scapula was determined by asking subjects to move the arm along a small circle beside the body. A series of instantaneous helical axes was derived from the changes in orientation and position of the humeral sensor relative to the scapular sensor, and the HH was calculated as the optimal pivot point of all the instantaneous helical axes[90].

The local reference systems were defined as follows: For the thorax-embedded reference system, the long-axis (Tz) was defined as the unit vector pointing from the midpoint of PX and T8 to the midpoint of SN and C7. The transverse axis (Tx) was defined as a unit vector perpendicular to the plane formed by C7, SN, and the midpoint between PX and T8, pointing toward the right side of the body. The sagittal axis (Ty) was the cross product of Tz and Tx. For the scapular-embedded reference system, the transverse axis (Sx) was defined as the unit vector pointing from SP to AA. The sagittal axis (Sy) was defined as a unit vector perpendicular to the plane defined by SP, AA, and IA, pointing forward. The long-axis (Sz) was the cross product of Sx and Sy. For the humeral-embedded reference system, the long-axis (Hz) was defined as the unit vector pointing from the midpoint of ME and LE to HH. The sagittal axis (Hy) was defined as a unit vector perpendicular to the plane formed by HH, ME, and LE, pointing forward. The transverse axis (Hx) was the cross product of Hz and Hy. Assuming that each of these local reference systems did not move with respect to the sensor attached to the corresponding segment, the orientation of the segment at any given instant during movement of the shoulder complex was determined in the global coordinate system.

Humerus rotation relative to the scapula was defined by angles $G\theta$, $G\varphi$, and $G\psi$ in the Hz-Hy-Hz sequence to represent glenohumeral horizontal abduction/adduction (Gh-HA: positive values indicating abduction), glenohumeral elevation/depression (Gh-EL: positive values indicating depression), and glenohumeral rotation (Gh-IR: positive values indicating internal rotation), respectively. Humerus rotation relative to the thorax was defined by $T\theta$, $T\varphi$, and $T\psi$ in the Hz-Hy-Hz sequence to represent humero-thoracic horizontal abduction/adduction (Ht-HA: positive values indicating abduction), thorax-humeral elevation/depression (Ht-EL: positive values indicating depression) and thorax-humeral rotation (Ht-IR: positive values indicating internal rotation), respectively. Scapular rotation relative to the thorax was defined by angles $S\theta$, $S\varphi$, and $S\psi$ in the Sz-Sy-Sx sequence to represent scapular protraction/retraction (positive values indicating protraction), scapular downward/upward rotation (positive values indicating downward rotation), and scapular anterior/posterior tilt (positive values indicating posterior tilt), respectively.

After a routine warm up, the c-ROM and the motion of front-crawl swimming were measured for each subject. The c-ROM measurement was taken in the laboratory setting. The transmitter was fixed to a custom-made wooden frame at a 1.0-m height (Figure 3.1A) and each subject was asked to sit on a chair placed right in front of the frame with the right elbow flexed approximately 90º. This arm position helped the subject to internally rotate the humerus with ease. Then, the subject was asked to elevate the arm completely with the humerus internally rotated maximally in a series of vertical planes throughout the physiological permissible range of the glenohumeral joint.

The front-crawl experiment was conducted in an indoor swimming pool. The experiment setup was same as what described in the Chapter 2, Method session. Each subject was asked to swim more than 10 stroke cycles with sub-maximal effort and a breath taken every two stroke cycles (after 10 stroke cycles, they were allowed to stop as they wished). The data collected in the fifth and the sixth stroke cycles (a stroke cycle with breathing action and a stroke cycle without breathing action) were used for analysis.

The Gh-IR angles determined in the c-ROM measurement were expressed as a function of Gh-HA and Gh-EL angles. This function was smoothed and interpolated using a cubic spline function to determine the c-ROM for each subject. Then, the glenohumeral configurations observed at every given instant of the fifth and sixth stroke cycles of front-crawl swimming were compared to the individual c-ROM. If the configuration was equal to or exceeded the c-ROM, the subacromial structures were considered to be subject abnormal stress. The excessive elevation was defined as the glenohumeral joint motion that exceed the maximum elevation angle recorded in the c-ROM measurement and the excessive internal rotation was defined as the glenohumeral joint motion exceeded the c-ROM. The time interval between two peaks of the Gh-EL angle defined stroke time. The time series data in the stroke cycle are expressed as the percentage of stroke time (with stroke cycle start defined as 0% of stroke time and the end as 100% of stroke time). To represent the duration of glenohumeral joint attaining at critical configuration, the period over which glenohumeral joint motion beyond the c-ROM during the two strokes was dividing by the total time for the two stroke cycles and expressed as a percentage of total time (%TT).

Since the present study focused on the overhead arm movement during swimming and the contact force in the glenohumeral joint was reported to be increased from shoulder height [16], the period over which the arm was located below the shoulder (the shoulder configurations with Ht -EL angle < 80º) was excluded from analysis and considered as to be contact free in glenohumeral joint.

The electromagnetic tracking device has been used widely for measuring scapular motion[20,91-93]. The measurement error was reported to range from 3º to 7º RMSE during humeral external rotation[94]. We conducted a series of pilot studies to test the reliability of the measurement. Reliability of digitizing the body landmarks was tested in four subjects and the RMSE was found to be 2.5 mm. This position error resulted in a RMSE of 1.0º for the Gh-HA angle, 2.5º for the Gh-EL angle, and 3.2º for the Gh-IR angle. The validity of the ROM was tested in four subjects by comparing independently measured maximal Gh-IR angles at three combinations of Gh-HA and Gh-EL angles to the corresponding values extracted from the ROM. The RMSE was found to be 6.6º.

3.3 Results

Glenohumeral, thorax-humeral, and scapulothoracic configurations changed systematically within each stroke cycle (Figure 3.2). The thorax-humeral configuration changed over a wide range, while the corresponding change in the glenohumeral configuration was limited to a narrow range. The mean value across subjects for the maximal Ht-EL angle value exhibited during front-crawl swimming was 153º ± 5º, while the mean maximal Gh-EL angle was 104º ± 10º. When the right arm was located above shoulder height (Ht -EL > 80º), the Ht -HA angle changed from -13º ± 10º to 83º ± 22º and the Gh-HA angle from -36º ± 8º to 18º ± 6º. A large range of scapular motion was observed during front-crawl swimming. The mean value across subjects for the maximal scapular upward rotation angle was 58 ± 10º. The scapular protraction angle changed from 10 ± 10º to 57 ± 13º. The maximal scapular posterior tilt and anterior tilt angles were 6 ± 9º and -21 ± 10º, respectively.

The excessive glenohumeral joint motion was observed in 15 subjects (88% of all subjects) with the mean duration of 7.7 ± 7.1%TT (range, 0% to 26%TT) during front crawl swimming. The excessive elevation was observed only in 2 subjects while the excessive internal rotation was observed in 15 subjects. The frequency distribution of the occurrence of excessive glenohumeral joint configurations during one stroke cycle is summarized for all subjects in the histogram (Figure 3.3). Subjects exhibited excessive glenohumeral joint configuration most frequently (13 out of 19 subjects) in the hand entry phase in which the arm was elevated high to enter into the water, and attending to the peak elevation angle at the end of hand entry phase. The next were in the stretch and out sweep phases (12 subjects in each phase) in which the arm maintained the submaximal elevation while maintaining a large arm internal rotation angle for stretch and catch the water. The subjects with no incidence of excessive glenohumeral joint motion exhibited either a large scapular upward rotation angle (up to 65º and 60º, respectively) in the stretch and end of recovery phase or a small posterior tilt angle (up to 0º and 2º, respectively) during the stroke phase. In contrast, the two subjects who had the longest duration of glenohumeral joint attaining at critical configuration (25.2% and 17.6% of the time spent in one stroke cycle, respectively) showed either a small scapular upward rotation (up to 60º and 38º, respectively) or a large scapular posterior tilt angle (up to 20º and 2º, respectively), especially in those phases in which a large arm internal rotation was required for pulling the water.

3.4 Discussion:

The present study described glenohumeral motion and identified the excessive glenohumeral joint motion during front-crawl swimming. The main findings are as follows: (a) subjects exhibited humero-thoracic and glenohumeral elevation angle up to 153° and 104°, respectively. Both of them are not as large as what is perceived from visual images. (b) the excessive glenohumeral joint motion was observed in 88% of all subjects and the duration of glenohumeral joint attaining at critical configuration was about 8% of the total stroke cycle time, and (c) the excessive glenohumeral joint motion occurred during the stretch phase, outsweep phase, the first half of the insweep phase, and the second half of the recovery phase.

The results of the present study supported the hypothesis that glenohumeral joint exceeds the physiologically permissible range of elevation and/or internal rotation during front crawl stroke cycle. A previous study reported that 75% of swimmers complaint shoulder pain during both stroke and recovery phase, especially at the hand entry into water[27]. The phases of which critical glenohumeral joint configurations were observed in the present study coincide with those swimming phases of shoulder pain in previous study. This suggested that the shoulder pain among swimmers might come from the excessive glenohumeral configuration which developed the risk of suffering abnormal stress in the joint. Yanai and Hay[26] examined the humero-thoracic motion during front crawl swimming and found that the arm moving beyond the range of motion at arm entry into the water, during the first half of the pull phase, and during the middle of the recovery phase with a duration of 25% of the time spent in one stroke cycle. The results of the present study which focused on the glenohumeral joint motion match their findings that the excessive shoulder motion occurs during multiple phases. However, the duration of excessive glenohumeral joint motion (7% of one stroke cycle) was substantially shorter than the result of extreme arm motion reported in the previous study [26]. This difference may be attributable to the model used; the previous study analyzed the motion of the humerus relative to torso whereas our study isolated motion at the glenohumeral joint.

The movement pattern of the glenohumeral joint observed during front crawl swimming of a given subject was found to differ substantially from the corresponding movement pattern of the humero-thoracic joint. This difference indicates that the movement pattern of the scapula did not follow a constant scapula-humeral rhythm throughout the stroke cycles. The shorter duration of critical joint motion observed in the present study than the previous study[26] might, therefore, be attributable to the movement pattern of the scapula not following the uniform scapulo-humeral rhythm during the stroke cycles. We re-analyzed our data to determine the duration over which the humero-thoracic configuration during front-crawl swimming exceeded the ROM of the humero-thoracic motion. If the humerus and scapula move in harmony with a ratio (i.e. scapulohumeral rhythm) unique to each individual [95-98], the outcome of the re-analysis should be the same as the original result.

Our re-analysis showed, however, the mean duration of humero-thoracic motion beyond the humero-thoracic ROM across subjects was substantially longer (22.6% ± 13.8% of the time spent for one stroke cycle; range, 0 to 47%) than our main results with the glenohumeral joint model (8%), and similar to that reported by Yanai and Hay who used a thorax-humerus model[26]. These results indicate that (a) the scapulo-humeral rhythm varied across the two measurements and (b) the scapula-humeral rhythm adopted/exhibited during the stroke cycles may help to prevent the glenohumeral joint from moving into a critical configuration in some phases of the stroke cycles.

On the basis of the literature, the glenohumeral joint structures at risk of developing abnormal stress was speculated from the arm positions during stroke cycles of front crawl swimming. In the hand entry phase, the peak glenohumeral elevation angle was attained during the stroke cycle similar as a Neer position, so a bone-to-bone contact stress may be developed between acromion and humeral shaft[54,55] and also to an internal impingement of the articular surface of rotator cuff and the labrum between the glenoid and the humeral head [51]. The excessive glenohumeral joint motion in this configuration was observed in 7 out of 17 subjects (41%). In the stretch phase, the arm attained at the submaximal as posture for modified Neer impingement test, so the contact pressure may be developed between supraspinatus ligament and coraco-acromial arch[16]. The excessive glenohumeral joint motion at this configuration was observed in 14 subjects (82%). In the outsweep phase, the arm flexed at shoulder height with arm rotated internally as the postures of Hawkins test, so the contact pressure may be developed between supraspinatus tendon and acromion and also between the articular surface of rotator cuff and glenoid[16,51]. The excessive glenohumeral joint motion for such configuration was observed in three subjects (18%). These findings indicate that in the glenohumeral joint the structures at risk of abnormal stress were not constant, but varied according to the arm postures during swimming stroke.

A limitation of this study is that motion was analyzed during resisted swimming rather than free swimming. Resisted swimming was reported to exacerbate shoulder pain[47], suggesting that the duration and intensity of subacromial impingement may be greater in resisted swimming than in unconstrained normal swimming. Future study is required to determine whether these results can be applied to front-crawl swimmers under normal conditions.

Conclusions:

The findings of this study support the following conclusions:

1) The peak values of both humero-thoracic and glenohumeral elevation angle are not as large as what is perceived from visual images.
2) The excessive glenohumeral joint motion was observed in the hand entry, stretch, the first half of sweep phases and the end of recovery phase lasting for 8% of the time spent in one stroke cycle. The hypothesis was sustained.
3) The glenohumeral joint structures at risk of developing abnormal stress during stroke cycles of front crawl swimming may vary across the stroke phases. In the hand entry phase the acromion and the tuberosity of humerus may be subject to bone-to-bone contact stress and the articular surface of rotator cuff and the labrum are subject to compressive stress due to internal impingement; in the stretch phase the supraspinatus

ligament may be subject to a contact pressure under the coraco-acromial arch; and in outsweep phase supraspinatus tendon may be subject to a contact pressure under the acromion and also to a compressive stress due to internal impingement.

Figures

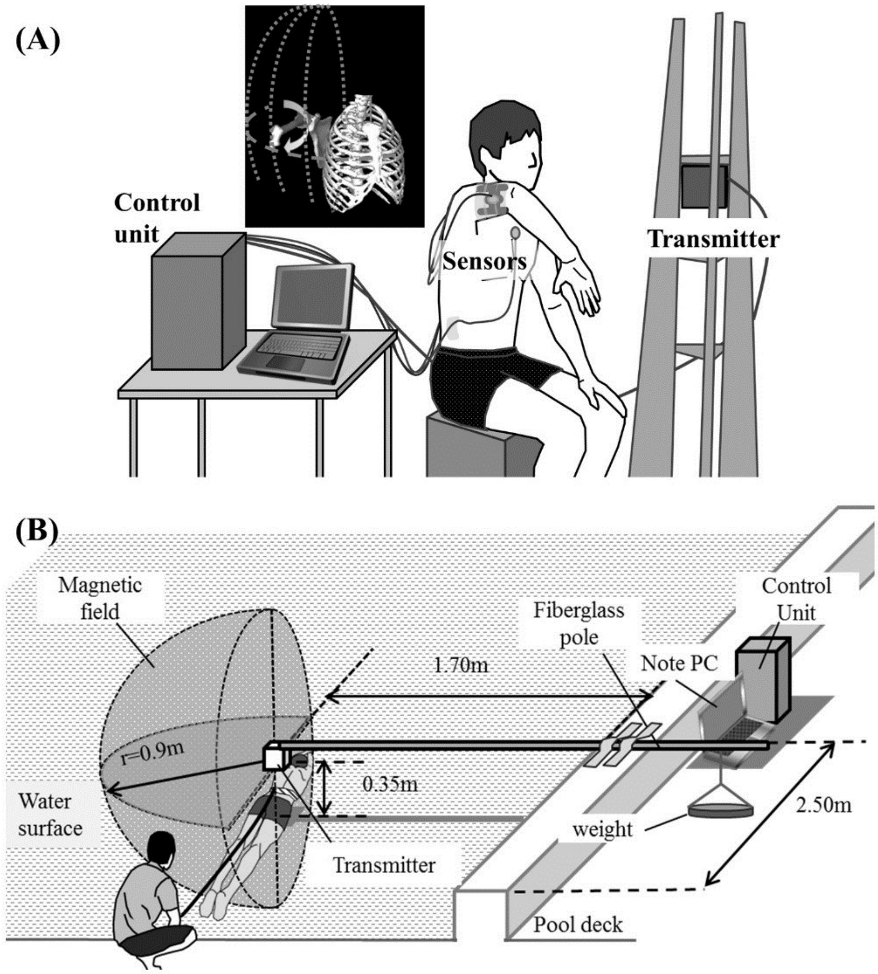

Figure 3.1: Experimental set up for the measurement of risk range of motion (ROM) (A) and front-crawl swimming (B).

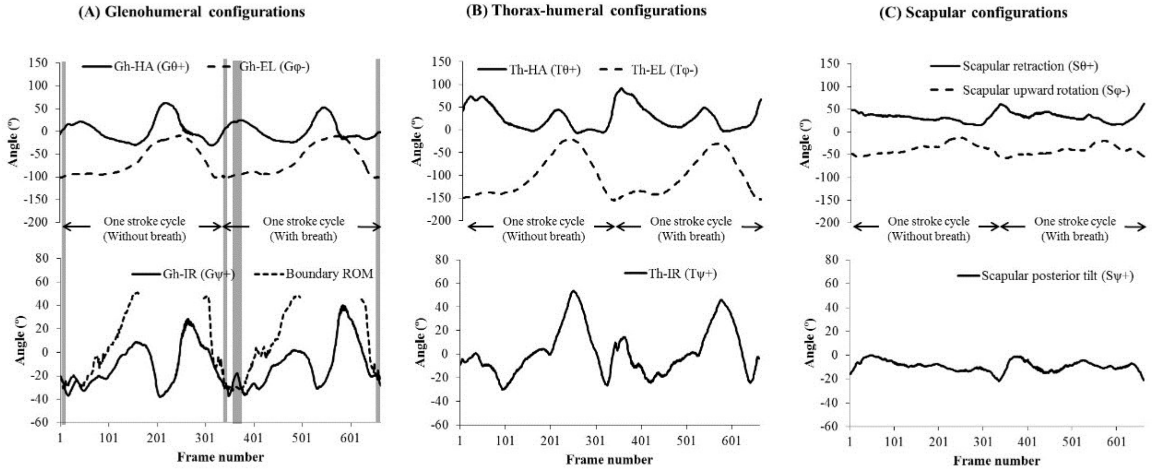

Figure 3.2: A typical example of shoulder movements during two consecutive stroke cycles showing the glenohumeral configurations (A), the thorax-humeral configurations (B), and the corresponding scapular configurations (C). The gray vertical bands indicate the periods of subacromial impingement.

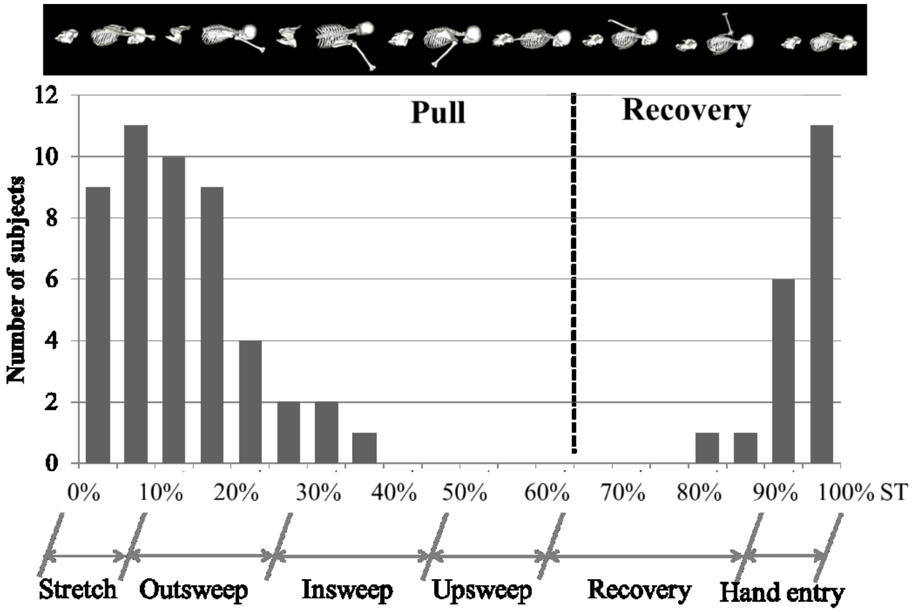

Figure 3.3: The number of subjects exhibiting impinged subacromial structures during one stroke cycle.

Chapter 4 General discussion

4.1 Summary of findings

The excessive joint motion has been proposed as the biomechanical factor related to overuse injuries in sports. In swimming, torso hyperextension and glenohumeral joint rotation beyond the physiologically permissible range of elevation or internal rotation have been postulated as the excessive joint motions responsible for low back pain and shoulder pain, respectively. However, no study has been conducted to determine the three-dimensional movements of low back and glenohumeral joint in swimming and, thereby, no evidence has been provided to evaluate if excessive joint motion occurs in swimming, when and how the excessive joint motion occurs during stroke cycles and the relation of excessive joint motion to overuse injuries. This thesis was aimed to determine the three-dimensional movements of torso and glenohumeral joint during front crawl swimming and to evaluate if these joint motions exceed the physiological range. The findings were expected to provide firm evidence to discuss the implication of the joint motion to the overuse low back pain and shoulder pain in swimming.

In the first study, a hypothesis that swimmers experience torso hyperextension consistently across the stroke cycles was tested. It was found that the largest torso extension angle exhibited during the stroke cycles was 9 ± 11° and it was recorded at or around (0.02 ± 0.08 s), the instant at which torso attained the largest twist angle. No participant hyperextended the torso consistently across the stroke cycles and subjects exhibited torso extension angles during tethered front crawl swimming that were much less than their physiological range of motion. So the hypothesis was rejected. The data suggested that repeated torso hyperextension during front crawl strokes should not be claimed to be the major cause of the high incidence of low back pain in swimmers.

In the second study, a hypothesis that glenohumeral joint internal rotated beyond the physiologically permissible range of motion during front crawl stroke cycle was tested. The excessive glenohumeral joint motion was observed in the hand entry phase, outsweep phase, the first half of the insweep phase, and the second half of the recovery phase for 88% of subjects with the average duration of 8% of the time spent in one stroke cycle. Among the subjects who exhibited excessive glenohumeral joint motion, the excessive elevation was observed in 2 subjects and the excessive internal rotation was observed in 15 subjects. So the hypothesis is sustained. According to literature, the shoulder structures being subjected to compressive and/or shear stress during the excessive glenohumeral joint motions varied across the stroke phases. In the hand entry phase the acromion and the tuberosity of humerus may be subject to bone-to-bone contact stress and the articular surface of rotator cuff and the labrum are subject to compressive stress due to internal impingement; in the stretch phase the supraspinatus ligament may be subject to a contact pressure under the coraco-acromial arch; and in outsweep phase supraspinatus tendon may be subject to a contact pressure under the acromion and also to a compressive stress due to internal impingement.

The findings of each study of the thesis have provided the evidence that the excessive glenohumeral joint motion occurs in resisted front crawl swimming while the excessive torso motion does not. The excessive GH motion occurs in the first half of pull phase and the end of recovery phase. It may cause GH structures at risk of developing abnormal stress during stroke cycles. However the observation of torso motion could not support the common proposal that low back pain caused by consistent torso hyperextension during swimming.

4.2 General discussion and suggestions

A reason that swimmers have been presumed to be hyperextending their torso during front crawl swimming may be due to that the complex three-dimensional movement. For example, when the torso performed a moderate extension of a twisted torso, even the angle between the longitude axes of thorax and pelvis was far below the physiological boundary, the rotation of the shoulder girdle has given observers wrong impression of the torso configuration in the oblique view from the pool deck (figure 4.1). Such misleading of the "excessive" joint motion in swimming may be give a wrong impression to coaches and trainer and may be cause an improper techniques adjustment.

The excessive glenohumeral joint motion was observed for most swimmers. However, interestingly, perceivable extreme motions at shoulder (e.g., extreme elevation in the stretch phase) were found to occur much less than the not-so-easily perceivable extreme motions (e.g., extreme internal rotation in sweep and recovery phases). In addition, both the humero-thoracic and glenohumeral joint elevation angle was not as excessive as the general image from visually observation. The large shoulder elevation with the torso lateral tilt towards the opposite side may give an impression of excessive shoulder elevation. While since the physiological range of shoulder internal rotated altered across the elevation and horizontal abduction angle (the higher arm elevated, the less internal rotation could performed)[34], it is difficult to judge the excessive internal rotation from visually observation during swimming. A looked-moderate shoulder configuration in the outsweep phase may be beyond the physiological permissible range. These results suggest that the coaches and trainers may fail recognize the risk of developing shoulder pain from the visually observation of the shoulder motion during swimming.

Therefore, because of the complex three-dimensional movement of the joint, the general impression of the perceivable extreme motion may misinterpret the “true” extreme joint motion in swimming and hide the risk of developing overuse injury from coaches and trainer. It suggested that the joint movement during swimming, also to those sports activities with complex 3D joint motion, should be determined in details and with considering the movement not in one plane but cross to the three dimensions.

4.3. The limitations of the thesis

4.3.1 Resisted front crawl swimming

In the present thesis, the electromagnetic tracking device (ETD) was used to determine the three-dimensional torso and glenohumeral joint motion. The ETD is a reliable and valid system for measuring the movements of scapulae[93,99]. Other methods for motion analysis such as a videography method or a motion capture system are not suitable for analyzing three-dimensional motion of body segments that slide freely underneath the skin surface, such as vertebrae, ribs and scapulae. However, the ETD system required all sensors attached to the body to be located within a small electromagnetic field generated by the transmitter, hence, free swimming could not be allowed for the swimmers. This requirement imposed a severe limitation to the study design: the swimmers need to be constrained to stay within the field while performing the strokes. In comparison with normal swimming, swimming with resistance was observed to have decreased stroke rate and stroke length, as well as an alteration in the ratio of phase durations,[80,81] although the techniques exhibited resisted-swimming may represent characteristic feature of the "real" swimming techniques for each swimmer[71,81]. To evaluate if the joint motions of low back and glenohumeral joint exhibited in resisted swimming could represent the "real" joint motion in normal swimming condition, we developed a system for moving the ETD underwater and tested the difference of torso and shoulder complex motion between the resisted swimming and a normal swimming condition. The details of the method was provided in the appendix.

The shoulder and torso motion during normal swimming was measured with the ETD for three swimmers from a swimming club (two of swimmers are male, and one is female). A comparison of the body movement was made between the resisted swimming and normal swimming condition for the swimmers. Each swimmer was asked to swim with the maximal effort in a normal swimming condition as well as in the resisted swimming condition. For each swimming condition for each subject, the peak values of torso and glenohumeral joint motions were compared between the conditions. The results showed that, the mean stroke time in the normal swimming condition was 1.19s/stroke, which was 0.03s less than the resisted swimming condition. The time-series data of the torso, right thorax-humeral configuration and right glenohumeral configuration in the two conditions showed similar movement patterns, while the peak values of joints motions altered across conditions for each subject (figure 4.5). The peak values of torso motion in the normal swimming condition were 24° in extension, 49° in left-to-right tilt and 56° in left-to-right twist, and the peak values of shoulder were 159° in thorax-humeral elevation and 127° in glenohumeral elevation. These values were slightly larger than the corresponding values in resisted swimming (the average differences were 9° in the extension, 7° in the left-to-right tilt and 10° in the left-to-right twist, 3° in thorax-humeral elevation and 7° in glenohumeral elevation). These differences of joint movement might be due to the different swimming conditions, such as the belt on the swimmer's waist might reduce the torso movement of swimmers in the resisted swimming; less leg sinking effect and body roll due to assistance of the tester to pull the swimmer in obliquely upward direction during the resisted swimming measurement. Although the kinematics of torso and glenohumeral joint altered between the conditions, the occurrences of the excessive motions in the two conditions were similar with applied a typical data of range of motion for torso and glenohumeral collected in the chapter 2 and 3. No constant torso hyperextension for swimmers in both conditions and the excessive glenohumeral joint motion was observed in the same phases between the conditions. These results suggest that the main findings in the thesis should not be altered by using the resisted-swimming.

4.3.2 The physical condition of subjects

The subjects participated in the studies of this thesis were the swimmers without any pain at the time of the measurements. Exclusion of injured swimmers might have caused the failure of observing excessive low back joint motions among the subjects.

Previous studies showed that the joint movement pattern was different between the patients with injury and the health population[59,100]. However, the cause- effect relation is not clear between the improper motion and injury. Excessive joint motions might damage some joint structures to cause injury whereas injury and/or pain due to the injury might cause alteration of joint motion in a given body movement. Therefore, even if excessive low back joint motions are observed from the swimmers who were suffering from an injury, this observation does not necessarily indicate the excessive joint motion is the cause of the low back injury. In the thesis, I focused on determining if the excessive motion occurred in swimming, and aimed to study how the pain or injury developed among the healthy swimmers with the excessive joint motion. So, only the movements of healthy swimmers could provide the evidence for the occurrence of excessive joint motion during swimming. However, the judgment to the hypothesis may not be strict enough without including the swimmers with low back or shoulder pain, future examination should be conducted for the swimmers with low back and shoulder pain.

Besides, the swimmers in the present thesis were provide enough time for rest before the swimming and were asked to swim with the maximal effort for just 13 stroke cycles which indicates about 50m or more short swimming distance. Therefore, swimmers were assuming to have enough energy to complete swimming with their maximal effort. The kinematic results may not represent the condition that swimmers are in fatigue. Although according to previous studies[101,102] the magnitude of body movement would be decreased when the subjects are fatigued, future study was needed to determine the excessive joint motion in the distance swimming and with the swimmers getting tired.

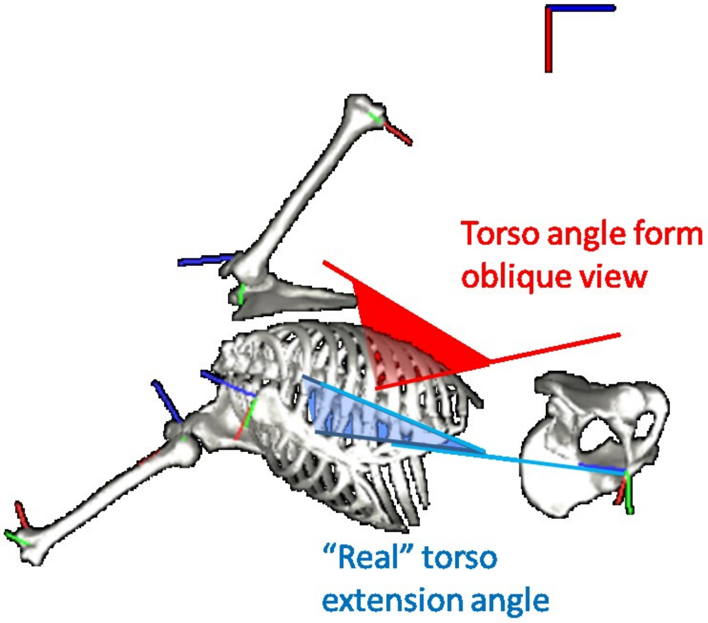

Figure 4.1— Different impressions of torso angle.

The torso angle observed from oblique view looks much larger than the "real" torso extension angle measured with an electromagnetic tracking device.

Appendix: A method for measuring swimming techniques with an electromagnetic tracking device

A.1 Introduction

Three-dimensional joint motion of shoulder and torso is important information to the biomechanical studies for swimming. The electromagnetic tracking device (ETD) is a reliable and valid system for measuring the movements of joint motion in three dimensions, especially convenient in the measurement of scapular motion[93,99]. Other methods for motion analysis such as a videography method or a motion capture system are not suitable for analyzing three-dimensional motion of body segments that slide freely underneath the skin surface, such as vertebrae, ribs and scapulae. However, the ETD system required all sensors attached to the body to be located within a small electromagnetic field generated by the transmitter, hence, free swimming could not be allowed for the swimmers. This requirement imposed a severe limitation to the study design: the swimmers need to be constrained to stay within the field while performing the strokes. In comparison with normal swimming, swimming with resistance was observed to have decreased stroke rate and stroke length, as well as an alteration in the ratio of phase durations,[80,81] although the techniques exhibited resisted-swimming may represent characteristic feature of the "real" swimming techniques for each swimmer[71,81]. To overcome this limitation, we developed a system for moving the ETD underwater and tested the accuracy of the system for measuring the related motion during a normal swimming condition. This new method would be used to measure the three-dimensional kinematics of body segments including scapulae during the normal swimming condition in future.

A.2 Method

An ETD (LIBERTY, POLHEMUS, VT, USA) consisting of a transmitter, a control unit, 6 sensors and a stylus was used for the data collection. The stylus is a pencil-shaped sensor to measure three-dimensional coordinates of the point touched by the pencil-shaped tip. The transmitter, sensors and stylus are gathered to the control unit with cables length of 6.10 m. A laptop computer was connected to the control unit and used for operating the device at the sampling frequency of 240 Hz for data collection. According to the factory specification manual, the ideal operating range of the magnetic field is within a hemisphere with radius of 2.13 m around the transmitter and the static accuracy within the ideal operating range is 0.76 mm in root-mean-square value (RMS) for position and 0.15° RMS for orientation.

We conducted the measurements in an indoor swimming pool (size 50 × 25 m and depth 1.3 to 4.0 m). As the metal frames behind the wall of the swimming pool which was expected to distort the magnetic field generated by transmitter of ETD, we set the transmitter at 2.0 m away from the pool side to minimize the measurement error due to this magnetic distortion. A custom-made cart (Creative Idea Sales, Co. Japan) was constructed to transport the transmitter, control unit and computer of the system so that the entire system could translate beside the sensor-attached swimming subject on a railway along the pool side (Figure A.1). The cart was made of aluminum L-beams, having a 0.5×0.4 m^2 base structure to which 4 wheels are attached at the four corners and a tower structure (height 1.0 m × length 0.3 m × width 0.3 m). A 2.5-m-long wooden pole was fixed horizontally on the top of the tower structure at one end and the transmitter was mounted on the other end. With this arrangement, the transmitter could be translated horizontally at 0.5 m above the water surface and 2.0 m away from the pool side. The control unit and the laptop computer were placed on the base structure of the cart. Sensors of the ETD were waterproofed professionally (STELLA Precision co. ltd., Japan).

The accuracy for measuring the related movement above and below the water surface during swimming around the transmitter was tested by using three self-made calibration plates. The calibration plate is a small wooden plate (size 50 × 120 mm) with two sensors fixed at a known distance apart and orientation to each other. The relative angle and distance between two sensors for each calibration plate was determined prior to the test. Three calibration plates were attached on the low back, left and right forearms of a swimmer by using double-sided tape and elastic medical tapes, respectively. Then, the swimmer performed front-crawl swimming along the 25 m course of the pool (depth of 4 m) while maintaining a constant distance of approximately 2 m from the pool side. To determine the mean velocity of the swimmer in the measurement, two markers were set on the pool deck at 3.0 m from each end of the course. When the swimmer passed by the markers, the synchronization signals were inputted manually to the ETD by the operator.

The swimmer was asked to swim two trials with his maximum effort twice (fast trails: mean velocity of 1.24 m/s and stroke frequency of 39.4 strokes/min) and another two trials with his medium effort (moderate trial; mean velocity of 0.84 m/s and the stroke frequency of 27.4 strokes/min). An operator pushed the cart to move on the railway, keeping the transmitter above the swimmer's back throughout each trial. Another operator walked on the pool deck beside the swimmer to hold a bundle of sensor cables so that the cables did not disturb swimming motion (Figure A.2).

The data collected between the two synchronization signals, i.e. the data collected in the 19 m session in the middle of the short course of the swimming pool, was used for analysis. Rotation angle and distance of one senor relative to the other for each calibration plate were calculated at every frame and compared with the known values. The difference was computed for each frame was determined as the error in measuring relative position and rotation between sensors during normal swimming condition. The root mean square error (RMSE) over all frames was determined to represent the error of measuring the position and orientation of each sensor for each trial.

A.3 Results

The result of the RMSE summarized from all data (the data of three calibration plates during all swimming trials) was 0.3° (ranged from -2.9° to 3.5°) for the orientation and 1.5 mm (ranged from -13.4 to 9.3 mm) for the distance. The absolute value of measurement error was less than 1.7° and 6.9 mm for 99.9% of data sets. The range of measurement error in both orientation and distance increased as the distance between the sensor and transmitter increased (Figure A.3). During the moderate swimming trials, the sensors used for calibration plate were moved in the range of 262 mm to 1443 mm around the transmitter; the RMSE for orientation and distance was 0.31º and 1.5 mm. During fast swimming trials, the sensors were moved in the range of 295 mm to 1308 mm around the transmitter; the RMSE were 0.28º and 1.4 mm (Table A.1).

A.4 Discussion

The accuracy in measuring segment motion during swimming with the video based methods has been reported in literature. Yanai et al[103] developed panning periscopes for determining three-dimensional body movement during swimming and tested the dynamic validity of the method by measuring the length of a scaled rod which was pulled through the measurement session. They reported that the mean error was ranged from 3.32 to 5.83 mm for each intersection of the rod. Another study[81] determined the dynamic measurement error with the static periscope system by using the similar method as Yanai et al. reported the RMS errors of 1.32 mm and 3.84 mm for above and under water area, respectively (0.44% and 1.28% of a 30 cm rod). Monnet et al. [104]used motion capture system to measure three-dimensional hand kinematics during swimming and determined the accuracy of the system by using a rigid bar composed of 10 markers in different direction. The RMS error for either in the air and underwater condition was up to 6.50 mm. Our results showed that the measurement error was within the error range of video based methods used for swimming analysis.

The accuracy of measuring body segmental movement with the ETD in dryland has been reported in literature. Meskers et al.,[93] calibrated the ETD by digitizing the markers with known position on a calibration frame in a 1 m^3 work space near the transmitter. They reported that mean error after calibration for each coordinate was up to 2.38 mm. Day et al.[105] calibrated ETD by setting sensors at known positions and orientations on the three-dimensional grid of a calibration frame, and then smoothed the measurement error with a linear regression model based on the known positions of the sensors. They reported the measurement error after smoothed was less than 1.2° and 18 mm with the error decreasing as the distance between the sensor and transmitter decreased. This error was suggested by them to be a proper range in biomechanics studies. Our result of measurement error with the ETD system underwater was as well as these studies of using ETD on dry land.

The shoulder and torso motion during normal swimming was measured with the ETD for three swimmers from a swimming club (two of swimmers are male, and one is female). A comparison of the body movement was made between the resisted swimming and normal swimming condition for the swimmers. Each swimmer was asked to swim with the maximal effort in a normal swimming condition as well as in the resisted swimming condition. In the normal swimming condition, the swimmers were asked to swim along the short course of the pool without wall kick. In the resisted swimming–condition, the swimmer was asked to perform 13 stroke cycles against the resistance applied by a rubber tube which constrained the swimmer to stay within valuable range near the fixed transmitter. The experiment setup for the resisted swimming was the same as the setup described in chapter 2 and chapter 3. For each swimming condition for each subject, the peak values of torso and glenohumeral joint motions in the fifth and sixth stroke cycle were recorded and the average values across the stroke cycles were determined to represent the subject's joint configurations. The values were compared between the conditions. The results showed that, the mean stroke time in the normal swimming condition was 1.19s/stroke which was 0.03s less than the resisted swimming condition. The time-series data of the torso, right thorax-humeral configuration and right glenohumeral configuration in the two conditions showed similar movement patterns, while the peak values of joints motions altered across conditions for each subject (figure A.4). The peak values of torso motion in the normal swimming condition were 24° in extension, 49° in left-to-right tilt and 56° in left-to-right twist, and the peak values of shoulder were 159° in thorax-humeral elevation and 127° in glenohumeral elevation. These values were slightly larger than the corresponding values in resisted swimming (the average differences were 9° in the extension, 7° in the left-to-right tilt and 10° in the left-to-right twist, 3°in thorax-humeral elevation and 7° in glenohumeral elevation). These differences of joint movement might be due to the different swimming conditions, such as the belt on the swimmer’s waist might reduce the torso movement of swimmers in the resisted swimming; less leg sinking effect and body roll due to assistance of the tester to pull the swimmer in obliquely upward direction during the resisted swimming measurement.

The results of the study indicate that the ETD is a valuable method to measuring the body segmental movements in normal swimming condition. Since the measurement error was found to increase as the distance between the sensor and transmitter increased, to reduce the measurement error due to the distance from transmitter, the ETD should be moved carefully to keep the transmitter following the swimmer closely during normal swimming measurement. Since the limitation of measurement range, the transmitter of the ETD should be moved with the swimmer in the measurement. Therefore, the system could only measure the relative movement of segments. The joint motion measured with this method cannot be described base on the inertial coordinates, or other attempts should be made, such as recording the position and orientation of transmitter with video based methods on dry land during the measurement.

Table A.1: RMSE for each calibration plate in each swimming trial

swimming trails	low back plate		right arm plate		left arm plate	
	roll (º)	distance (mm)	roll (º)	distance (mm)	roll (º)	distance (mm)
moderate1	0.3	1.6	0.5	2.0	0.3	1.6
moderate2	0.2	0.8	0.4	1.7	0.2	1.1
mean	0.3	1.2	0.4	1.8	0.3	1.4
fast 1	0.3	1.2	0.4	1.6	0.2	1.1
fast 2	0.2	1.0	0.4	1.9	0.2	1.6
mean	0.2	1.1	0.4	1.7	0.2	1.3

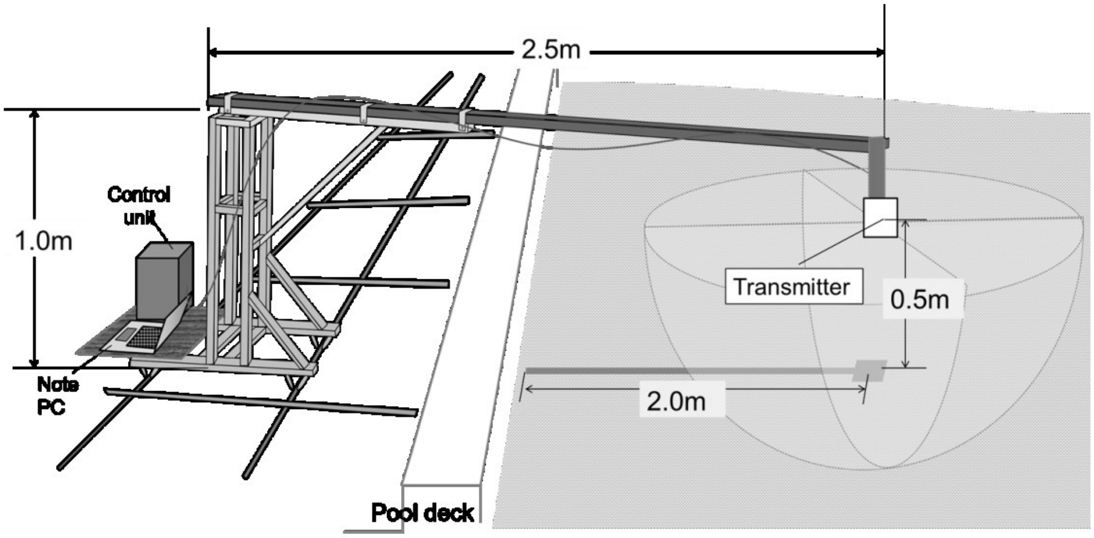

Figure A.1: Set-up of electromagnetic tracking device

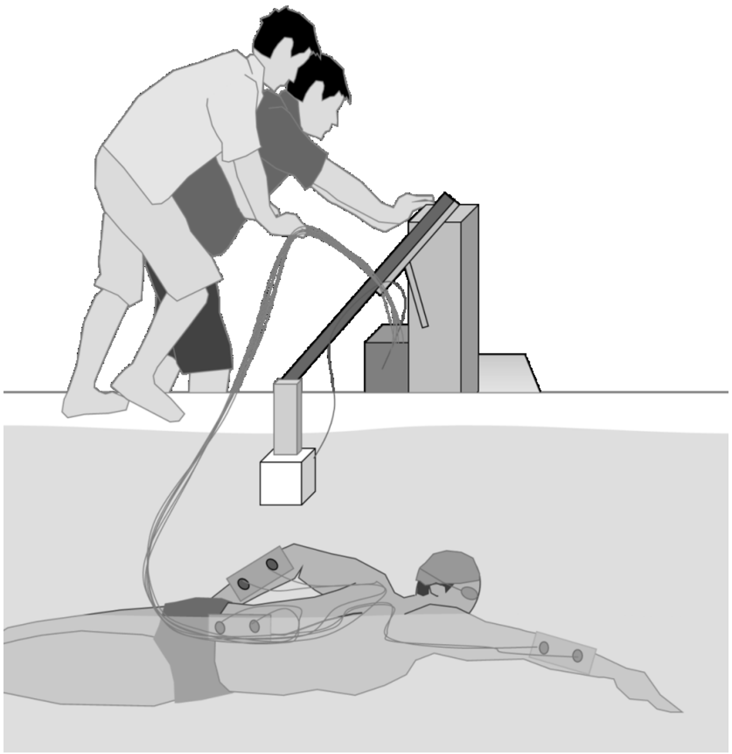

Figure A.2: Image of operating the electromagnetic tracking device during swimming measurement

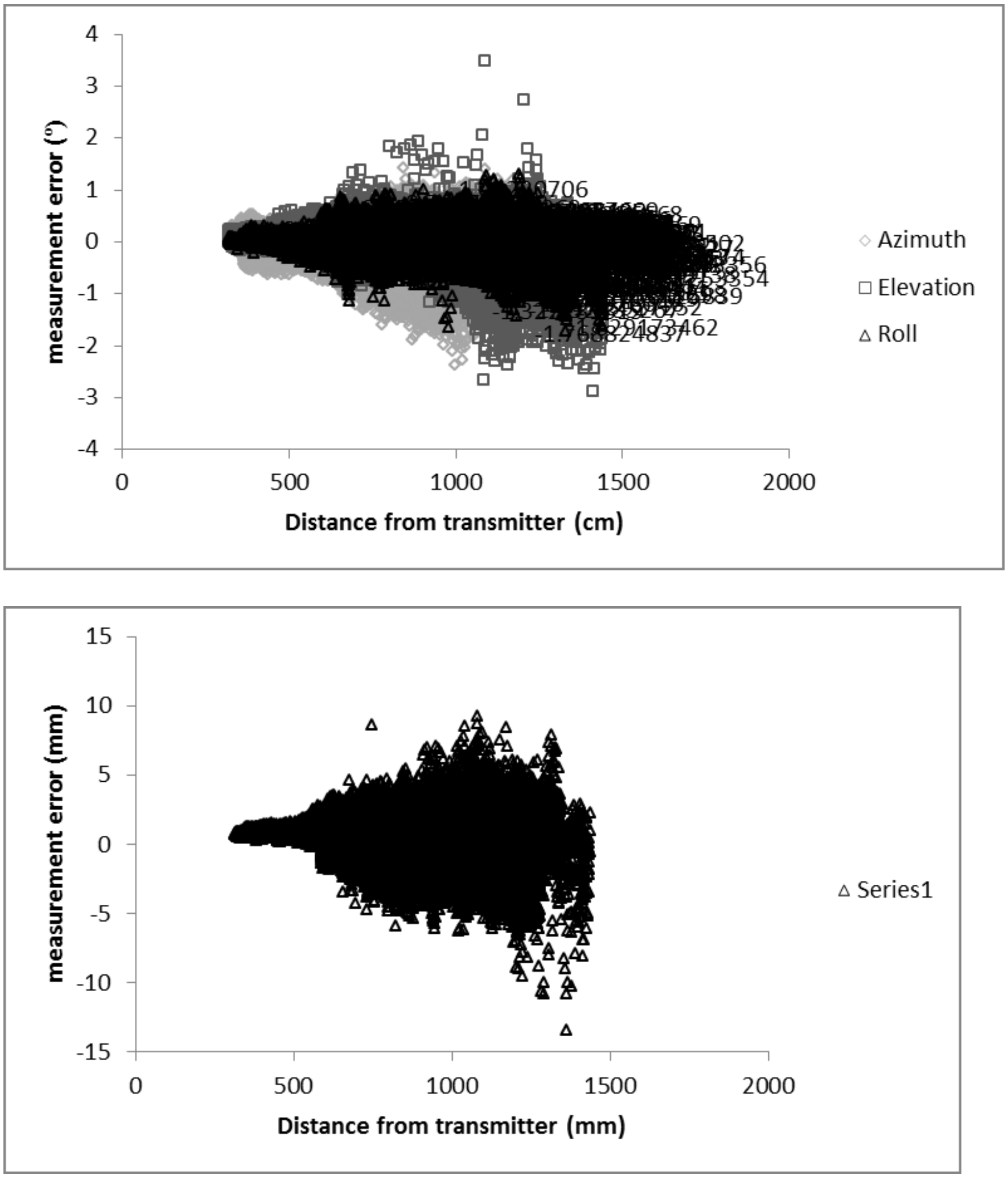

Figure A.3 Plots of measurement error in orientation (upper one) and distance (below one) with the distance of sensor from transmitter.

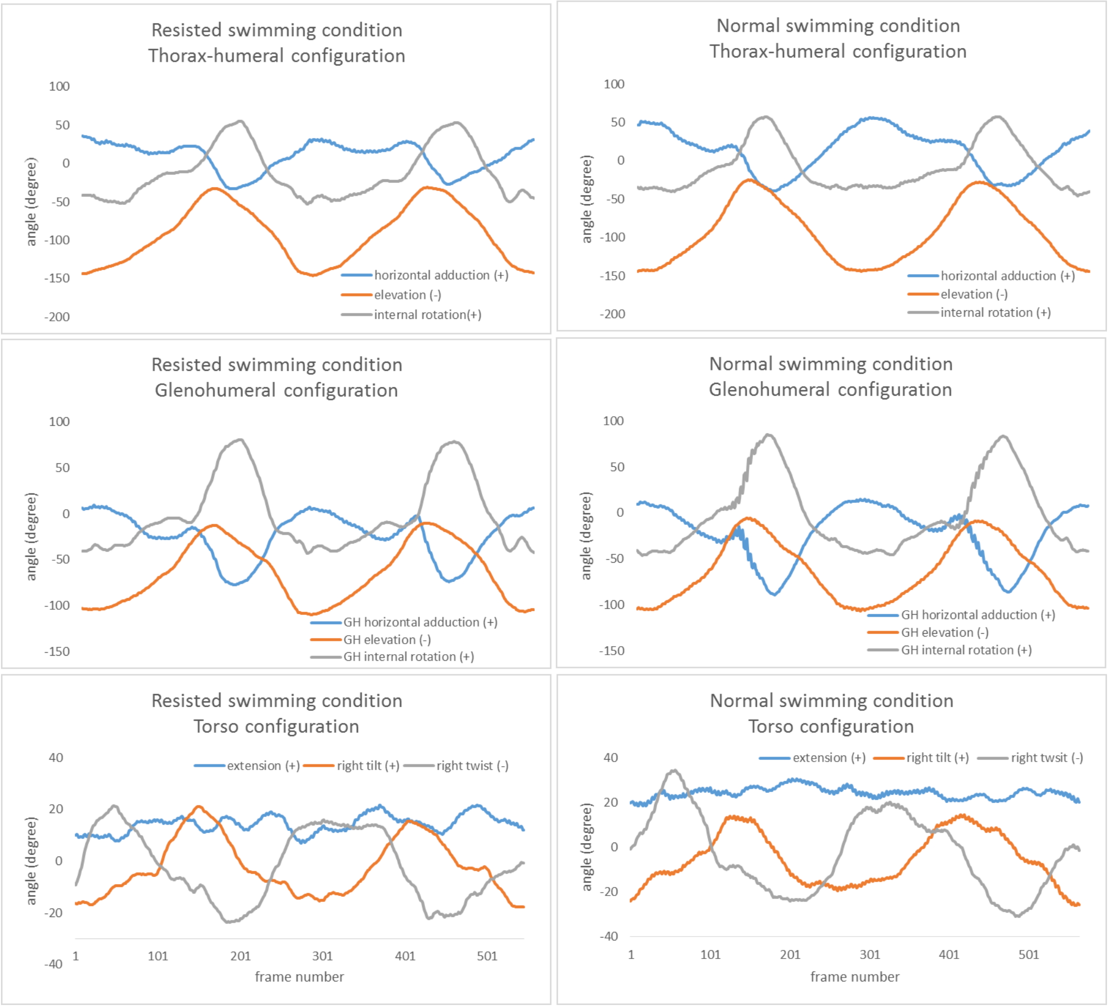

Figure 4.5— A typical example of the three-dimensional motion of torso and shoulder complex during resisted and normal front crawl swimming conditions.

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