공학석사학위논문

User-specific Tennis Racket Selection Method by Use of Motion Capture and Dynamic Analysis

모션 캡쳐와 동역학 해석을 통한 개인 맞춤형 테니스 라켓 선정 방법

2014**년** 2**월**

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

User-specific Tennis Racket Selection Method by Use of Motion Capture and Dynamic Analysis

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Among many properties of tennis racket, moment of inertia (MOI) is a crucial property to consider when choosing a racket, as it may not only affect the power of a stroke, but also potential for injury. A careful choice of the property can be made by feeling the racket weight while swinging it, but this process is too subjective and is not accurate for nonprofessional tennis players. Therefore, more objective and generalized method is needed for tennis players of various playing levels.

The purpose of this study is to propose a new method of selecting the optimal MOI of a racket that maximizes the post-impact ball speed while preventing upper limb injuries, through kinematic analysis and dynamic analysis of the forehand swing motions with different racket MOI. Motion capture was performed on forehand motion of 3 skilled tennis players for 5 different racket MOI, and then kinematic analysis and dynamic analysis were done to determine the racket swing speed at the time of impact and the peak torque applied on shoulder, elbow, and wrist joints. A simple racket-ball collision model which follows conservation of momentum law was used with the racket swing speed to predict post-impact ball speed. Isokinetic measurement was done on the shoulder, elbow, and wrist joint motions to normalize the peak torque values determined from the dynamic analysis. This study discusses how these post-impact ball speed and the normalized peak torque values can be used to evaluate racket MOI on each individual player. This study proposes an idea of normalized joint torque limit, which is the percentage of the joint strength allowable in repetitive sports such as tennis, and this idea was implemented to set the joint torque limit for each player. By doing so, the racket MOI with maximum post-impact ball speed while below normalized joint torque limit could be found for each subjects. The value of the normalized joint torque limit needs to be corrected based on experimental data in the future study, and this would improve the method for more accurate racket selection.

keywords : Tennis racket, Moment of inertia, Dynamic analysis, Motion capture
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Chapter 1

Introduction

For over decades, tennis has become one of the most popular sports worldwide. The growth of tennis population has invigorated racket industries and as a result, wide variety of rackets are available today. These rackets vary in properties, such as mass, moment of inertia, and rim stiffness, and this wide choice of properties allow players to choose a racket that fits his or her play style and body condition.

According to Groppel, playing tennis with efficiency requires an optimal racket which allows the player to perform at high level, while lessening the stress on muscles and joints [1]. Hence, considering both performance and potential for injury is essential when a player choose a tennis racket.

There have been many studies on the relationship between racket properties and racket performance. Racket properties, such as racket string tension, frame stiffness, and moment of inertia have been studied to find their influence on racket performance [2-7]. Amongst these racket parameters, moment of inertia (MOI) of a racket has been reported by many studies as an important property which affects the performance of the racket [5-7]. According to Cross, when a rod was swung with maximal effort, the swing speed was found to be independent of the mass of the rod, but on the other hand, the swing speed was highly correlated with the MOI of the rod [5]. From another study by Cross, the ratio between the exit ball speed and the incoming ball speed is known to be strongly correlated with the MOI of the racket about an axis passing through the racket handle [6]. Additionally, Whiteside claims that the racket MOI about an axis perpendicular to the racket handle and in the plane of the racket, also known as “swing weight” [8], affects the serve kinematics as the peak shoulder internal rotation and wrist flexion velocities were decreased with increased swing weight [7]. The MOI of a racket therefore, affects the swing kinematics, and should be considered in racket selection in order to improve one’s playing performance.

Many studies also focused on the effect of MOI on the potential for injury. The most common injuries in upper extremities during swing motion are known to be shoulder rotator cuff and elbow epicondylitis (tennis elbow) [9-10]. A computer simulation study by Nesbit showed that increase of MOI of a racket significantly influenced elbow loading during forehand swing motion [11]. Additionally, Creveaux's inverse dynamics analysis on shoulder joint moment during serve motion implies that using rackets with inappropriate inertial properties may lead to upper limb injuries [12]. Therefore, MOI of a tennis racket not only affects the performance of the player, but also the potential for upper extremities injuries.

The studies mentioned above provide general tendency of how racket MOI affects the swing performance and the potential for arm injuries. With such tendency alone, choosing a racket MOI is still an ambiguous process, because we are all different in anthropometry, and in joint strength. Additionally, a study by Knudson found that there exists variability in forehand swing kinematics among different players [13]. With such reasons, certain racket MOI may be optimal for one player, but not for the others. Currently, rackets are being chosen by actually using the implement and evaluating it based on the player's feeling. Although feeling is an important criterion in selecting the racket, this may lead to an inaccurate decision as the sensitivity level on the racket MOI varies significantly with playing level [14]. Therefore, a more detailed and objective analysis is needed in order to determine the optimal racket MOI which an individual player can benefit the most.

This study aims to propose a quantitative method of finding the racket MOI which allows an individual to perform at maximum level while avoiding dangers of injuries. In order to determine the optimal racket MOI, the following 3 factors of an individual were considered:

① Forehand swing kinematics
② Anthropometry
③ Joint strength

With the listed inputs, rackets of different MOI were evaluated by determining how fast the ball speed is after impact, and how much of the joint torques relative to the individuals strength are required on the arm joints to produce such performance. The method proposed by this study uses motion capture and dynamic analysis to conduct such evaluation.

This paper consists of 6 chapters. Chapter 2 of this paper gives overall description of the racket selection method, while chapters 3 and 4 provide information on how experiments were conducted and how data was analyzed. The results of the proposed method applied to the 3 subjects participated in this study are presented in chapter 5 along with discussion, and lastly, chapter 6 concludes the paper with summary and limitations of the study that could be improved in the future research.

Chapter 2

Overview

The racket selection method proposed by this study has an ultimate goal of evaluating rackets of different MOI property with consideration of the 3 given characteristics of an individual: forehand kinematics of swinging each racket, anthropometry, and joint strength profile. Figure 1 shows an overview of the evaluation process where the 3 factors are used as inputs along with the racket property.

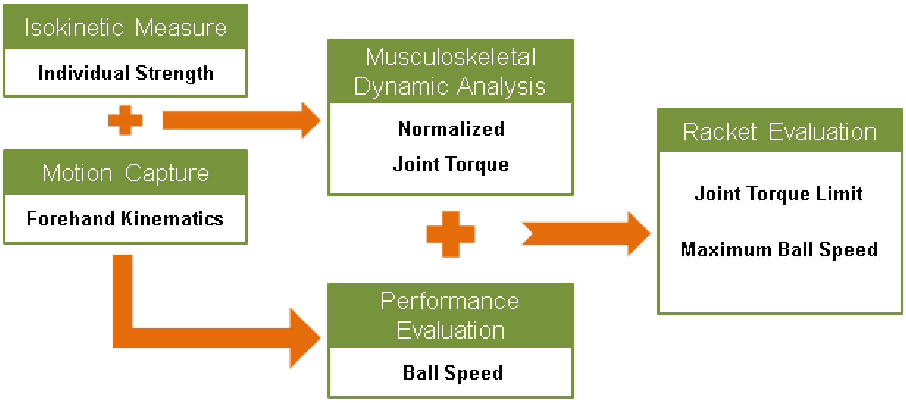

Figure 1 An overview diagram of the racket selection method.

As can be seen in figure 1, the method consists of 2 experimental process and 2 analytic process. First, motion capture was conducted on corresponding player to gain kinematic data of the racket movements and his or her forehand motion when using rackets of various MOI properties. Then, joint strength profiles of shoulder, elbow, and wrist were determined by isokinetic measurements. Kinematic analysis was done on the racket movement to predict the post-impact ball speed and this was used to evaluate racket performance. Kinematic data of the swing motion and anthropometric data was then used for dynamic analysis to determine the peak joint torques applied at each arm joint. The peak joint torques were then normalized by the joint strength and they were used to evaluate potential for injuries of upper limb joints. Based on the evaluation, the optimal racket MOIs for all 3 participants in this study were found.

Chapter 3

Experimental Methods

The study comprises of two experiments: motion capture and isokinetic measurement. Motion capture was conducted to gain kinematic data of the participants performing forehand swing motion with rackets of various moment of inertia (MOI). Additionally, the kinematic data of the rackets was also recorded to be used for performance evaluation. Isokinetic measurement was then performed to measure the joint strength of each participants, which will later on used for normalization of the peak joint torques determined from dynamic analysis of the forehand motion.

3.1 Motion Capture

Motion capture experiment was conducted to collect kinematic data of individual players performing forehand swing motion for 5 rackets with different moment of inertia properties. Three male players (age 28.0±6.1, mass 69.8±6.0kg, height 174.5±1.7cm) participated in this study. All three subjects were highly skilled with at least 10 years of consistent playing experience. None of the subjects suffered from any injury or disorder on muscles, tendons, and joints.

3.1.1 Racket Preparation

Five rackets with different MOI properties were used in this experiment. All five rackets were chosen to be Head MicroGEL Radical Midplus [15] (Head NV, Netherlands and Austria) in order to constrain all other properties, such as racket stiffness, string tension, and mass. On each of the five rackets, lead tape of 36g was attached at different locations along the beam of the racket. By doing so, the MOI of all five rackets differed from each other while still keeping the total mass the same. The locations of the lead tape can be seen in figure 2.

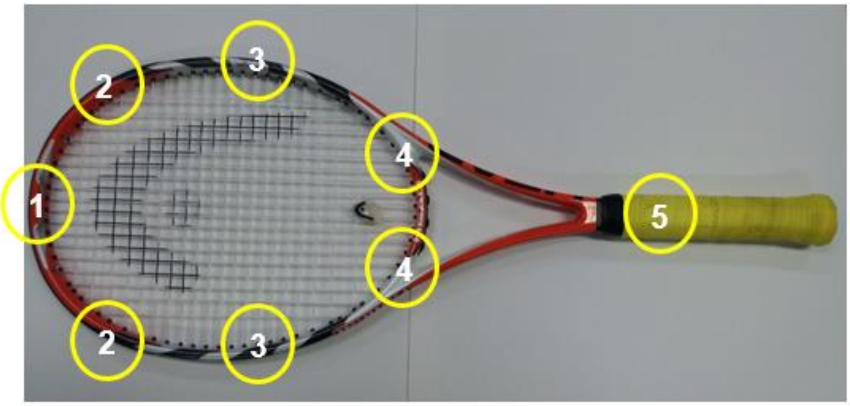

Figure 2 Locations of the lead tape attached. Each number represents the attachment locations for each racket number

The mass of all 5 rackets after lead tape was attached was 371.8g, and the moment of inertia properties of all 5 rackets are summarized in table 1. The moment of inertia values were determined about the three principal axes located at the racket center of mass, and these axes are shown in figure 3. The three axes are Iz axis perpendicular to the plane of the racket, Ix axis in line with the long direction of the racket, and lastly, Iy axis perpendicular to other two axes.

Table 1 MOI of 5 rackets. The MOI was determined about the 3 principal axes located at the center of mass

Racket	I_x (kg m^2)	I_y (kg m^2)	I_z (kg m^2)
1	0.0014	0.0174	0.0188
2	0.0017	0.0165	0.0181
3	0.0019	0.0144	0.0163
4	0.0015	0.0137	0.0152
5	0.0014	0.0151	0.0165

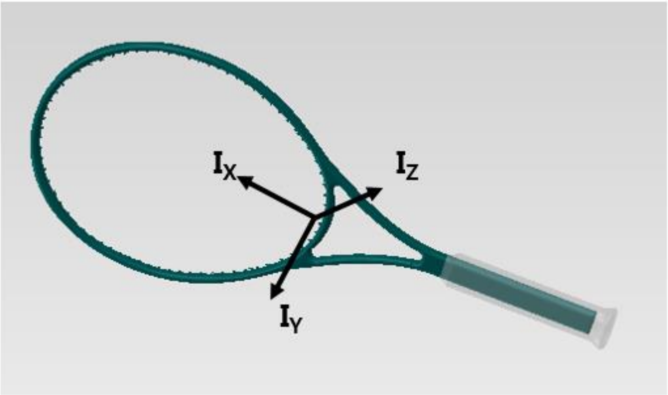

Figure 3 Three principal axes located at center of mass

3.1.2 Experimental Procedure

23 reflective markers were attached to both arms, pelvis, and torso of each subject based on the standard plug-in gait marker set. Additionally, 4 additional markers were attached to the racket at the far tip, both sides, and on the grip. The location of the markers attached to the subjects and the rackets can be seen on figure 4 and 5. By doing so, the marker trajectory data of the body of the subject performing forehand motions and the racket movement could be recorded. The trajectory data of the markers attached was recorded by 15 VICON T160 infrared (IR) cameras [16] (VICON, UK) at sampling frequency of 100 Hz.

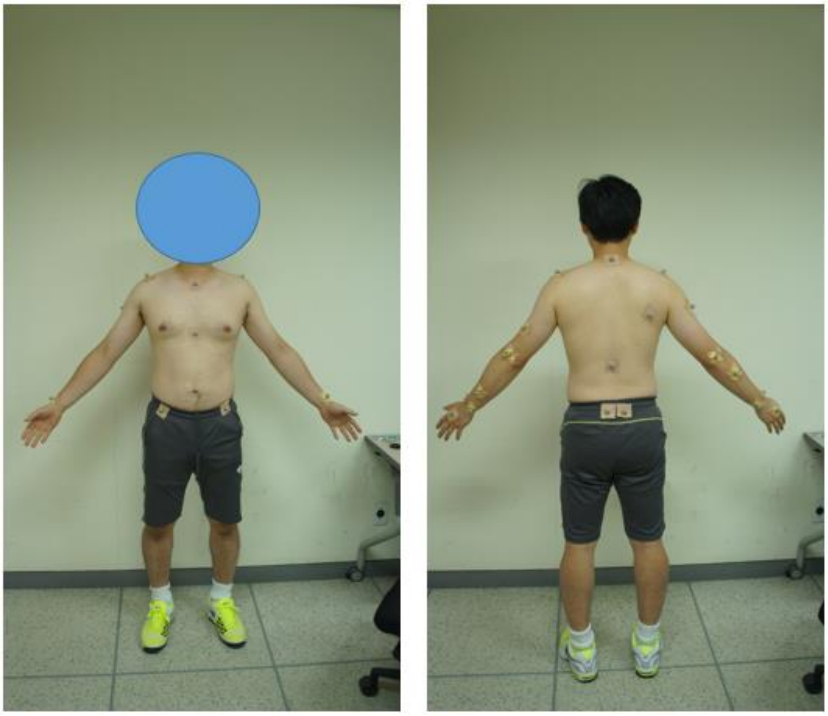

Figure 4 Marker placements on the subject’s upper body and pelvis.

Figure 5 Marker placements on the racket.

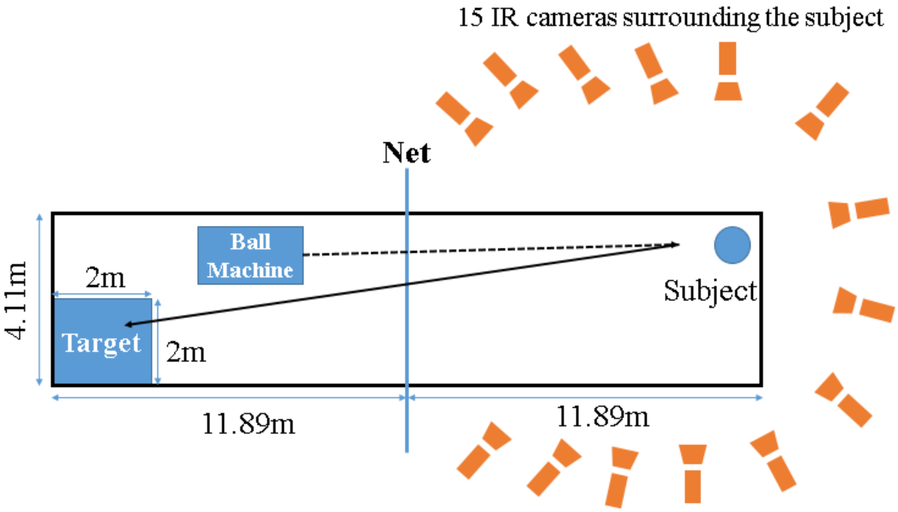

Figure 6 Experimental setting of the motion capture.

Figure 6 shows the experimental setting of the motion capture experiment. Tennis balls were fed to the subject by the ball machine located at the other side of the court with the speed of 8.6 m/s. Subjects were instructed to hit the ball to the targeted area with size of 2m by 2m located as shown on the figure. Before proceeding to the actual experiment, the subjects were given 30 minutes of warm up time with their own rackets to allow them to feel comfortable hitting to the targeted area in the court.

After warming up, the subjects were given one of the 5 prepared rackets randomly and were given 20 trials of hitting to get used to the new racket. In the actual trials, with motion being captured, the subjects were instructed to hit the balls with maximal effort. Maximal effort was demanded to the subjects for the purpose of keeping the kinematics as consistent as possible, because the forehand kinematics can be altered by varying post-impact ball speed which is directly related to the effort given on the swing, according to the study by Seeley [17]. Each set consisted of 10 trials, and total of 5 sets were carried out for each racket. Between each set, 1 minute resting time was given, and between each racket, 5 minutes of rest was given to allow subjects to recover from fatigue.

Trials which the subject was able to hit the ball in the target area was marked as success, and only the data of successive trials was used in the kinematic and dynamic analysis. The marker positions captured by the IR cameras were recorded as 3 dimensional position data by using Vicon Nexus software [18] (Vicon, UK). The recorded marker data were to be used for kinematic analysis of the racket movement, and dynamic analysis of the body movement during forehand motion.

After motion capture was done, subject’s length of arm segments and torso segment, width of pelvis, height, and weight were measured to be used in dynamic analysis.

3.2 Isokinetic Measurement

The maximal joint torques at the arm joints that can be produced by each subject were measured. These values were used to normalize the calculated joint torques that were found to be required for corresponding forehand motions. Therefore, for each joint motion, the percentage of the maximal joint strength could be calculated, and this value gives an implication on how much effort was needed to swing the corresponding racket.

The maximal joint torques were determined through isokinetic measurements. An isokinetic measurement is the measure of maximal muscular torque when constant angular velocity is applied to the corresponding joint motion. The measurements were conducted by using Biodex System 3 [19-20] (Biodex Medical Systems, USA). The isokinetic profile of each subject was measured on glenohumeral internal rotation, elbow flexion, and wrist flexion, as these are the primary joint motions during forehand motion. Figures 7~9 illustrate how the isokinetic measurements were conducted on the 3 joint motions.

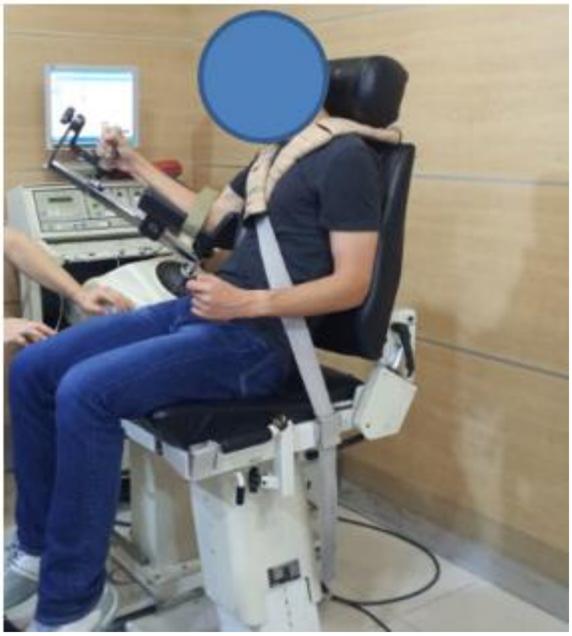

Figure 7 Isokinetic measurement of glenohumeral internal rotation

Figure 8 Isokinetic measurement of elbow flexion

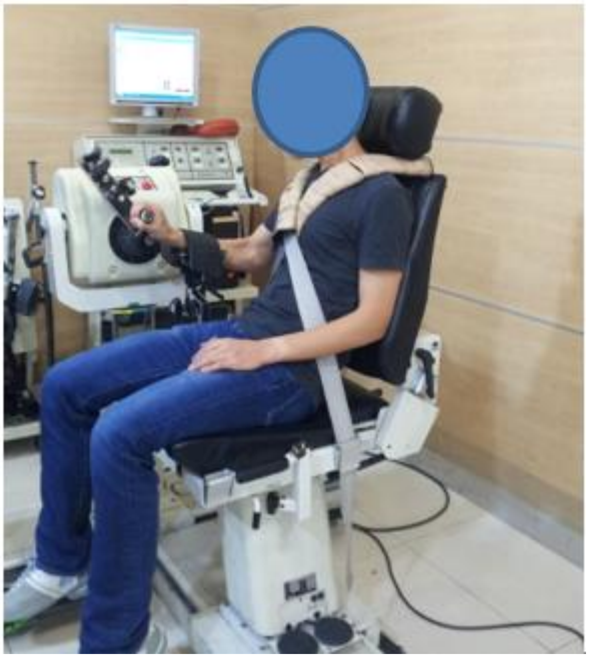

Figure 9 Isokinetic measurement of wrist flexion

Chapter 4

Data Analysis

The marker position data and isokinetic profile of each subject were used to determine the post-impact ball speed and normalized joint torques activated on shoulder, elbow, and wrist joints. In order to do so, the marker data collected from motion capture experiment was analyzed.

The marker data of the body and racket was used to determine the joint kinematics through the process of inverse kinematics, and then inverse dynamics calculation was conducted using the joint kinematics information to determine the joint torques applied to each body joint during the forehand swing motion. Finally, the peak torque values were analyzed through normalization, using the isokinetic profile of each subject, to evaluate the potential for arm joint injuries.

The position data of the markers attached to the rackets was also used to calculate the racket swing speed at the point of impact, which was then applied to a simple racket-ball impact model to determine the post-impact ball speed.

4.1 Dynamic Analysis

Dynamic analysis was conducted using the marker position data recorded during the motion capture experiment. Each marker attached to the body and the racket has its own trajectory, however, the markers recorded are not classified, because the IR cameras cannot recognize that they are all different markers serving for different purposes. Therefore, the markers need to be labelled with proper names in order to be used in further analysis. Figure 10 shows the raw marker data before any classification was done.

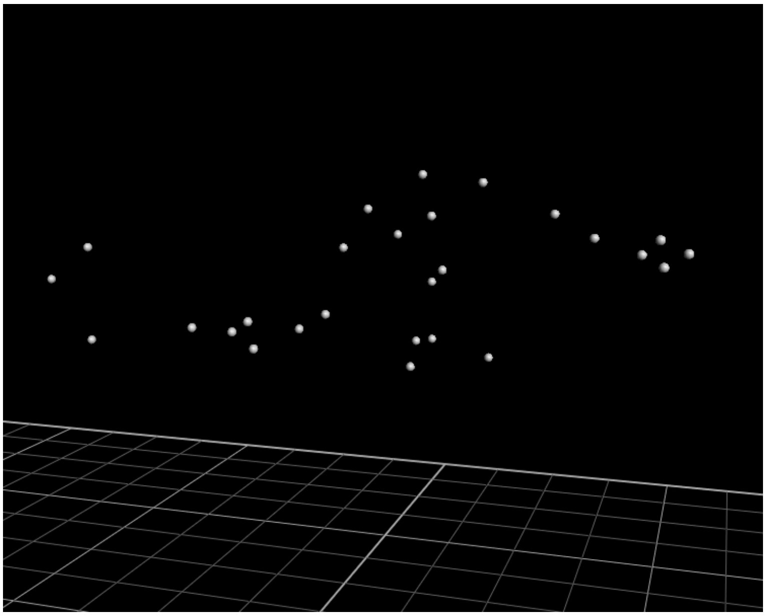

Figure 10 Marker data before classification.

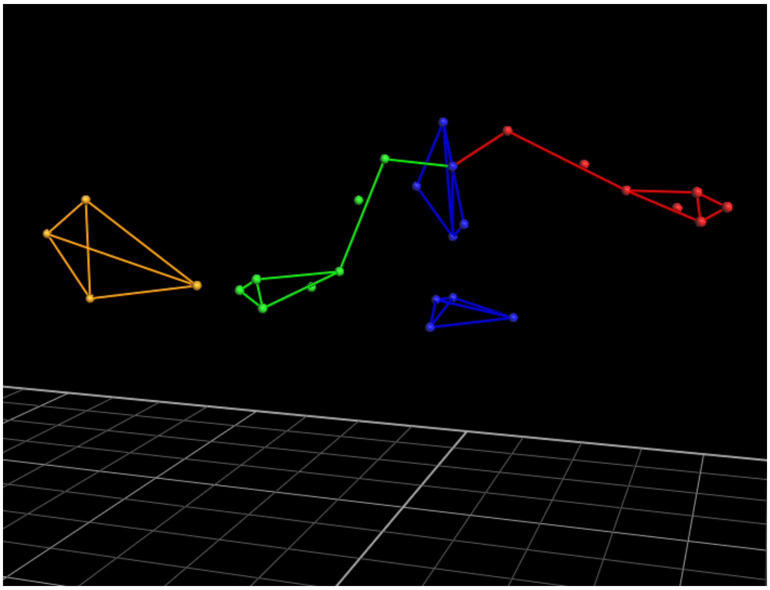

Figure 11 Marker data after labelling

The labelling process was performed by using Vicon Nexus software, and figure 11 illustrates the result of labelling process. The markers are labelled with different color to help understand the purpose of each marker. The labelled marker trajectory data was then exported as .c3d file type for dynamic analysis.

The .c3d file containing the marker trajectory information was then imported to AnyBody Modeling System [21-22] (AnyBody Technology A/S, Denmark), which is a human musculoskeletal dynamic simulation software used for analyzing human movements. Using AnyBody Modeling System, the forehand motion was reconstructed by solving inverse kinematics. The human model, ‘GaitFullBody’ which is provided by AnyBody Modeling System was used for this process. Since lower extremities of the body were not part of the interest in this study, the model was edited to exclude both legs. Through inverse kinematics, the forehand motion was reconstructed by minimizing the coordinate errors between the markers defined on the model and the markers measured from motion capture. This minimization of the marker errors was also used to scale the model to the actual segment sizes of the subjects.

From the reconstructed forehand motion, joint angle, joint angular velocity, and joint angular acceleration were determined which allows the use of equations of motion to solve for joint torques:

$$\mathrm{M(q)}\ddot{q} + C(q, \dot{q}) + G(q) = \tau \tag{4.1}$$

Where, *M(q)* is the mass matrix of the system, $q, \dot{q},$ and $\ddot{q}$ are the joint angle, angular velocity, and angular acceleration, respectively, $C(q, \dot{q})$ is coriolis and centrifugal force vector, $G(q)$ is gravitational force vector, and τ is the joint torque vector. The inverse dynamics analysis process using AnyBody Modeling System is illustrated in figure 12.

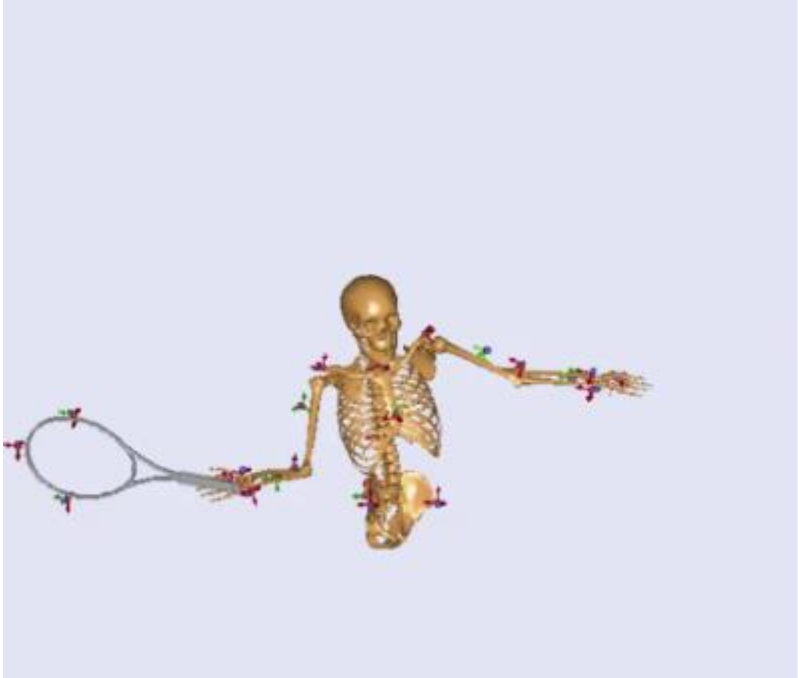

Figure 12 Inverse dynamics analysis using AnyBody Modeling System

In order to apply the effect of inertial properties of the actual rackets, a tennis racket segment was added in the model as can be seen on figure 12, and the inertial properties of the rackets were included in the segment information.

After inverse dynamics calculations, peak torque values of glenohumeral internal rotation, elbow flexion, and wrist flexion were determined, and normalized to the isokinetic profile of the corresponding subject to evaluate the potential for injury of each racket. The normalized joint torque of each joint motion was evaluated by defining the limit, where any normalized joint torque exceeding the value is considered not safe from injuries. Unfortunately, there has not been any study about the percentage of the maximal joint strength, which causes injuries during repetitive sports motion, such as tennis. Therefore, in this study, the limit value was assumed to be 0.9, which is 10 percent less than the maximal joint strength. This is the limitation of the method proposed by the study, and this value needs to be determined in future studies based on experimental data. The corrected value of the normalized joint torque limit would improve the accuracy of the method.

4.2 Ball Speed Calculation

The ball speed after impact was calculated by using a physics model that follows the momentum conservation laws. According to the study by Cross, a tennis racket can be simplified as a rigid body when it is assumed that the ball impacts along the long axis of the racket, because the effect of vibration energy loss gets reduced significantly [6]. The ball speed after impact was not directly measured with speed gun, or high speed camera, because the impact point on the racket would have varied among the trials. Varying the impact point significantly changes the ball speed as the vibration energy loss takes effect, therefore, the impact point needs to be kept constant in order to compare between rackets. Just by using the racket kinematics, this study aims to compare rackets by constraining the impact point at the sweet spot, and predict the post-impact ball speed by using the racket-ball collision model introduced by the work of Cross. The simplified model of the racket-ball collision is shown in figure 13. From the work of Cross, the ball speed after the impact from the simplified model can be expressed as follow by using momentum conservation laws:

$$v_2 = (1 + e_A)V_1 + \ e_A v_1 \tag{4.2}$$

$$e_A = \frac{v_2}{v_1} = \frac{eM_e - m}{M_e + m} \tag{4.3}$$

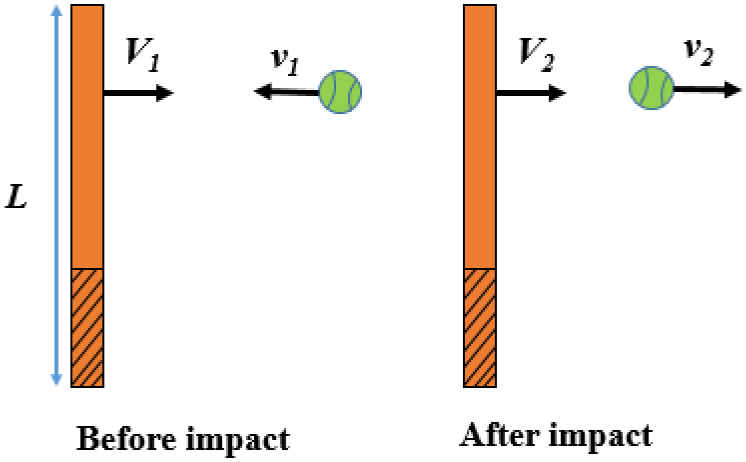

Figure 13 Simplified racket-ball collision model

The outgoing speed of a ball, v_2 is a function of the racket intrinsic power, e_A, racket swing speed at impact, V_1, and the incoming ball speed, v_1. The value of e_A can be determined by equation 4.3, where e is the coefficient of restitution, M_e is the effective mass at the impact point, and m is the mass of a tennis ball. For impact at the center of the head of the racket, M_e can be well estimated with $M_e \approx I_{10}/(L-26)^2$ where I_{10} is the swing weight about an axis 10 cm above the bottom of the racket, and L is the length of the racket. The value of e is known to be approximately 0.85 for typical racket-ball collision without considering string tension and racket stiffness. This assumption is valid as all rackets used in the experiment had the same string tension and racket stiffness.

The speed of the racket was determined by using the trajectory data of the markers attached to the both sides of the racket head during the motion capture experiment. Figure 14 highlights the two markers. The position data of the impact point at the center of the racket head was determined by calculating the midpoint of the two markers. The speed of the racket head center was then determined by differentiating the midpoint trajectory, where racket head speed at impact was found to be the maximum. With the racket speed, V_1 determined, along with the calculated e_A and the measured v_1 of the ball fed to the subjects by the ball machine, the outgoing speed of the ball could be determined by equation 4.2.

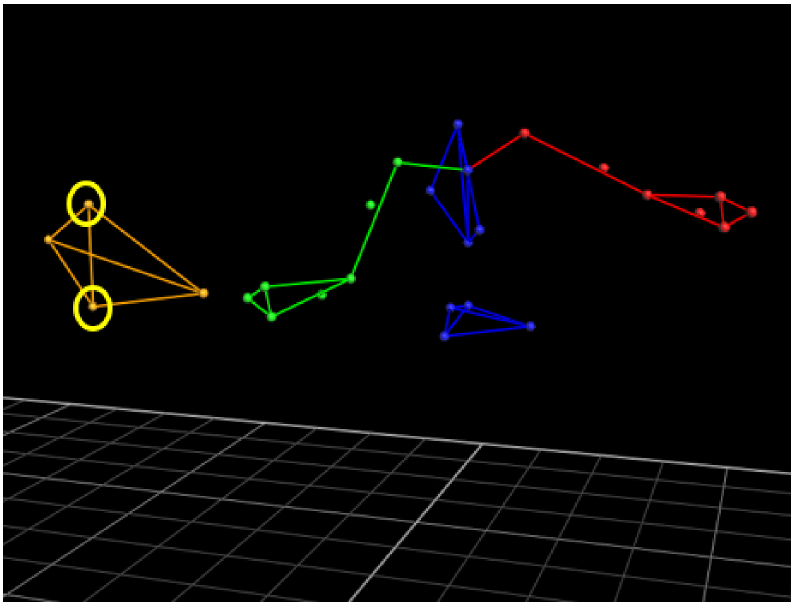

Figure 14 Racket head speed was determined by using the midpoint of the two markers attached at both sides of the racket head.

Chapter 5

Results and Discussion

5 rackets were evaluated for each subject by calculating the post-impact ball speeds and normalized joint torques on glenohumeral internal rotation, elbow flexion, and wrist flexion. In this chapter, the results of the performance measure, which is the ball speed, and the potential for injury measure are displayed. The optimal rackets were found for which the post-impact ball speed was the fastest while the normalized joint torques for all 3 joint motions were below the limit.

5.1 Performance

The performance that each of the 5 rackets had brought to each subject was determined by calculating the outgoing speed of the ball after racket-ball impact. As mentioned, the ball speed when it was hit at the sweet spot of the racket could be predicted by using equation 4.2. The calculated ball speeds of the 5 racket MOIs about an axis perpendicular to the racket handle and in the plane of the racket (swing weight) are shown in figure 15~17 for all 3 subjects participated in this study. The error bars represent one standard error of the trials for each racket.

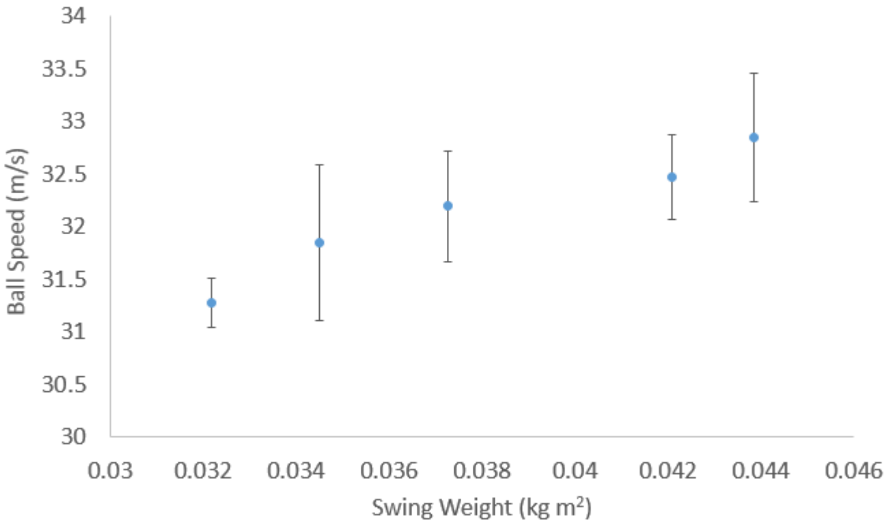

Figure 15 Ball speed for subject 1

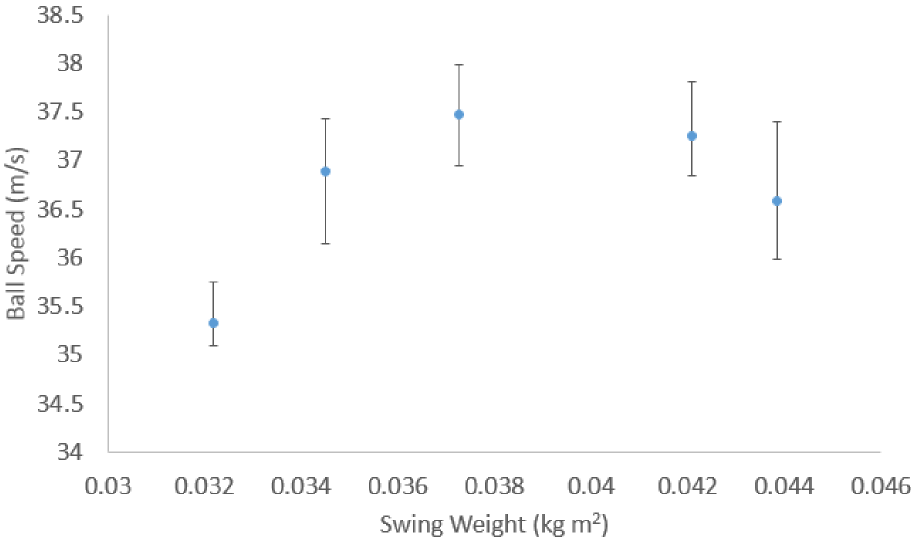

Figure 16 Ball speed for subject 2

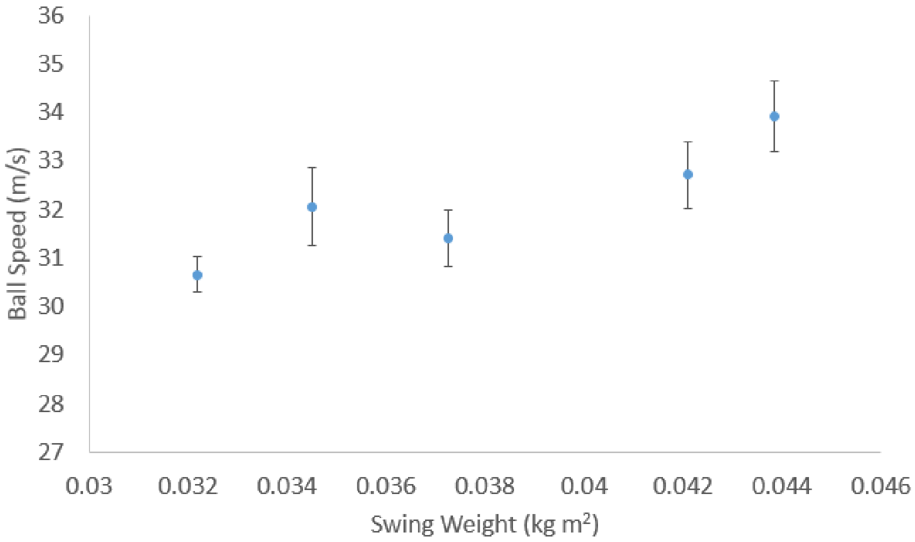

Figure 17 Ball speed for subject 3

As can be seen in the figure 15~17, the outgoing ball speed tends to increase with the swing weight of the racket for subject 1 and subject 3 with the maximum speeds resulting at the swing weight of 0.044 kg m^2. On the other hand, subject 2 showed ball speed increasing until the swing weight of 0.037 kg m^2 and then showed decrease in speed for heavier rackets.

It has been known that the racket can be swung with higher speed for lower swing weight [5], while the power factor that is intrinsic to the racket improves with higher swing weight [6]. This implies that subject 1 and subject 3 were able to perform better with the biggest racket MOI (or swing weight) because the effect of increase in racket power overwhelmed the effect of decrease in racket speed. The result of subject 2 implies that the effect of increase in racket power could not overwhelm the effect of decrease in racket speed as the racket got heavier than the swing weight of 0.037 kg m^2.

5.2 Potential for Injury

Dynamic analysis was conducted for the 5 MOIs to calculate the peak joint torques activated for glenohumeral internal rotation, elbow flexion, and wrist flexion during forehand swing motion. The peak joint torques for each joint motion were evaluated by first normalizing to the isokinetic joint strength and then comparing the normalized values to the predefined normalized joint torque limit of 0.9. If any normalized joint torque value exceeds 0.9, the corresponding racket moment of inertia and above were considered to have potential for injuries. Table 2 summarizes the isokinetic joint strength of all 3 subjects, and table 3~5 shows the normalized peak torques.

Table 2 Summary of the isokinetic joint strength of glenohumeral internal rotation (GIR), elbow flexion (EF), and wrist flexion (WF). Units are in N-m.

Joint Motion	Subject 1	Subject 2	Subject 3
GIR	36.2	34.9	40.6
EF	15.3	31.6	29.7
WF	16.6	17.1	15.7

Table 3 Peak joint torques normalized for subject 1

MOI (kg m^2)	GIR	EF	WF
0.0322	0.562	0.346	0.693
0.0345	0.757	0.610	0.718
0.0373	0.772	0.706	0.801
0.0421	0.805	0.557	1.022
0.0439	0.759	0.560	0.918

Table 4 Peak joint torques normalized for subject 2

MOI (kg m^2)	GIR	EF	WF
0.0322	0.572	0.861	0.726
0.0345	0.634	0.997	1.192
0.0373	0.519	0.938	0.929
0.0421	0.595	1.002	1.035
0.0439	0.555	0.968	0.868

Table 5 Peak joint torques normalized for subject 3

MOI (kg m^2)	GIR	EF	WF
0.0322	0.535	0.663	0.306
0.0345	0.724	0.744	0.481
0.0373	0.701	0.778	0.366
0.0421	0.715	0.803	0.376
0.0439	0.808	0.772	0.569

The results of the dynamic analysis showed that for normalized joint torque limit of 0.9, there is potential for injuries for racket MOI of 0.0421 kg m^2 and above for subject 1, as the peak joint torque value of the wrist flexion exceeded 0.9 for both rackets. For subject 2, only the racket MOI of 0.0322 kg m^2 was safe from potential for injuries as the other rackets showed peak torque values higher than the limit at elbow flexion. Lastly, subject 3 was found to be safe from overdoing himself for all rackets as the peak torques values were all below the limit. These results were combined with the performance result to find the optimal racket that brings highest ball speed with safety. Figure 18~20 shows the result of the evaluation.

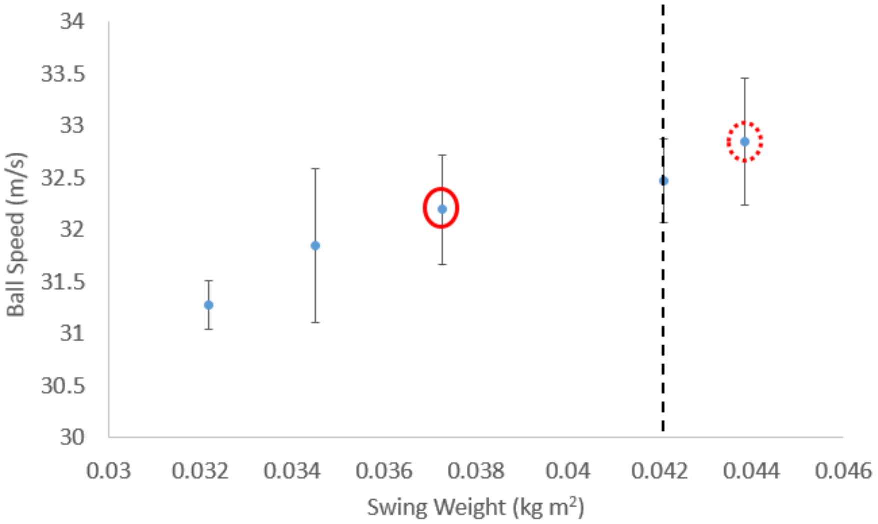

Figure 18 Evaluation result for subject 1. Broken circle represents the racket with highest ball speed when only performance was evaluated. Solid circle represents the racket with highest ball speed when both criteria was considered. The broken vertical line represents the racket which normalized peak torque exceeded the limit.

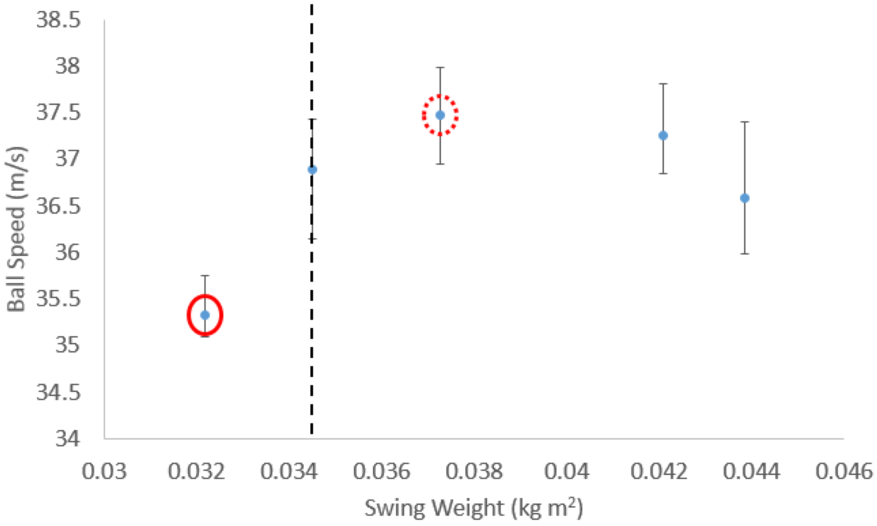

Figure 19 Evaluation result for subject 2.

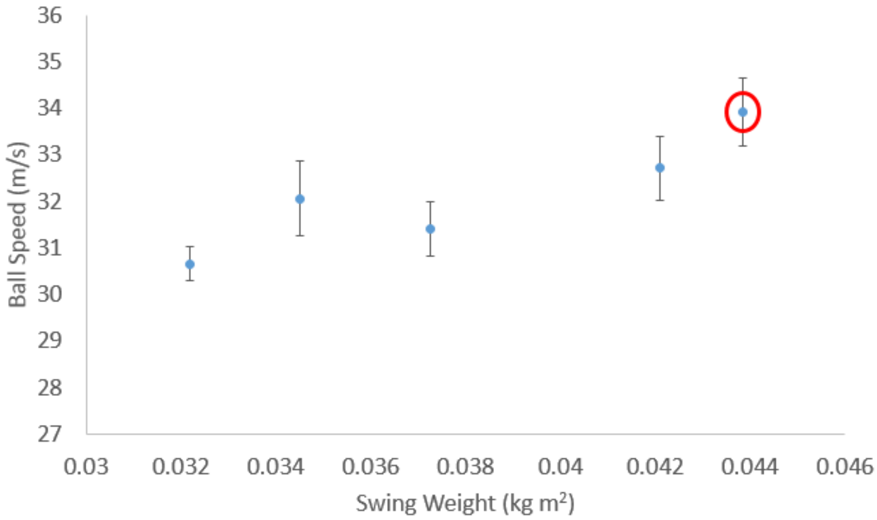

Figure 20 Evaluation result for subject 3

As can be seen on the figure 18~20, subject 1 and subject 2 showed highest ball speed when the racket MOI was 0.0439 kg m^2 and

0.0373 kg m^2 respectively. However, when normalized peak joint torque was evaluated, the optimal racket has changed to 0.0373 kg m^2 and 0.0322 kg m^2 respectively.

These results imply that although a racket may result in a very high ball speed, the effort that needs to be given by the player may be too high for safety. Therefore, both racket performance and potential for injuries need to be carefully considered when choosing a racket. The relationship between the ball speed and the racket MOI also seemed to vary among subjects. Hence, a player should not choose a racket based only on the racket speculations, but should choose a racket that brings the maximum synergy among the player's swing style, strength, and the racket property.

There exist some limitations on this study that could be improved upon in the future. First, the normalized joint torque limit was assumed to be 0.9 on purpose to introduce a new method of choosing racket MOI based on the performance and safety criteria. The future work is needed for determination of the limit for repetitive sports activities through experimental study. By doing so, the method introduced in this paper would give results with better accuracy. Secondly, experiments could be done on more various inertial properties. Lastly, the racket-ball impact modeling could be incorporated to the dynamic analysis for more accurate joint torque determination.

Chapter 6

Conclusion

A quantitative method of determining the optimal racket MOI was introduced in this study. Individual’s forehand swing style and anthropometry were applied to the method through motion capture, and maximal joint strength was applied through isokinetic measurement. The performance was evaluated by using racket kinematics and racket-ball impact model. Safety of the racket was evaluated by conducting dynamic analysis of the swing motion for each racket MOI. As a result, the optimal racket MOIs for all 3 participants in this study were found to be different from each other, implying that performance and safety of the racket need to be evaluated in order to find the racket that fits individual’s swing style, strength, and anthropometry. Although some limitations exist, this method is meaningful in a sense that it was the first to propose a quantitative and objective way which could replace the conventional subjective method which relies on the player’s feelings on the racket. The future improvement on dynamic analysis through application of racket-ball collision model and correction of the normalized peak torque limit would allow this method to be more accurate on selecting the racket MOI which the players can benefit the most from.

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초 록

테니스 경기 능력 향상을 위해 테니스 라켓 선정은 매우 중요한 과정이며, 특히 라켓의 주요 성질 중 하나인 관성 모멘트를 잘 선정하는 것이 중요하다. 라켓을 고르는 방법은 사용자가 직접 사용해 본 후 느낀 점을 통해 자신에게 가장 적합한 라켓을 선정하는 것이 일반적이다. 하지만 이는 매우 주관적인 방법이며 숙련자가 아닌 경우에는 이러한 방법으로 선택하기가 어렵다. 따라서, 다양한 실력의 사용자들을 위한 일반화된 라켓 선정 방법이 필요하다.

라켓의 선정 시 고려하게 되는 주요 요소는 성능과 부상으로부터의 안전성인데, 이는 라켓의 주요 성질 중 하나인 관성 모멘트와 개개인의 스윙 특징 및 신체조건의 영향을 받는다. 따라서, 본 연구에서는 모션 캡처와 개개인의 스윙에 대한 동역학적 분석을 통해서 가장 좋은 성능을 보인 동시에 부상으로부터 안전한 라켓의 관성 모멘트를 선정하는 방법을 제안한다. 이를 구현하기 위해 3명의 숙련된 테니스 동호인을 대상으로 5가지 관성 모멘트 성질을 갖는 라켓을 이용한 포핸드 동작에 대해 모션 캡처를 수행하였으며, 이를 이용한 기구학적 분석 및 동역학적 분석을 진행하였다. 개개인에 대한 라켓의 성능을 평가하기 위해 스윙 동작 시 라켓의 움직임을 분석하여 라켓 스윙 속도를 계산하였고, 계산된 결과를 이용하여 운동량 보존 법칙에 의거한 물리적 충돌 모델을 통해서 타격 후 공의 속도를 계산하였다. 라켓의 안전성을 평가하기 위해서는 각각의 라켓을 휘둘렀을 때의 동작을 동역학적으로 분석을 하

여 어깨, 팔꿈치, 그리고 손목에 발생하는 관절 모멘트를 계산하였으며, 이 값들을 개개인의 등속성 측정으로부터 얻은 최대 관절 모멘트에 대해 정규화하였다. 이렇게 정규화된 값을 통해 자신이 낼 수 있는 힘의 몇 퍼센트를 사용했는지를 분석함으로써 라켓의 안전성을 평가하였다. 본 연구에서는 이러한 두 가지 평가 항목을 함께 적용하여 사용자에게 안전성이 확보되고 성능이 제일 좋은 라켓을 선정하는 방법을 제안하였으며, 이를 통해서, 라켓 사용 시 얻은 느낌에만 의존하지 않고 더욱 객관적으로 라켓을 선정할 수 있을 것으로 기대된다.

주요어 : 테니스 라켓, 관성 모멘트, 동역학 분석, 모션 캡처
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