On-site Personal Sport Skill Improvement Support Using only a Smartwatch

Guillaume Lopez[1], Shohei Abe[1], Kengo Hashimoto[1] and Anna Yokokubo[1]

***Abstract*— In recent years, with the widespread use of wearable devices, in the sports field and the like, research and techniques for analyzing the movement are being developed by attaching sensors to a body or a gear and analyzing the movement from the acquired data. However, most of them require dedicated sensors and post-processing by computers. Also, there is nothing to do on the spot to provide feedback for form and skill improvement. In this research, we developed a sports skill improvement support system using smartwatch sensors and feedback screen. We verified whether it can be utilized in everyday life. In order to demonstrate the versatility of sports skill improvement support, we implemented application software targeting two movements, baseball pitching action and tennis' serve action. Designed and implemented so that analysis and feedback can be presented solely by smartwatch worn on the wrist of the dominant arm without having a paired smartphone so that the user can perform the usual operation. As a result of the verification experiments, both average and maximum ball speeds increased for all the subjects with respect to the pitching motion. Concerning serve motion, a significant improvement of the pronation movement capability was observed. These results demonstrate the effectiveness of smartwatches as an individual skill improvement support system in sports where arm movement is greatly related to skills.**

I. INTRODUCTION

In recent years, lifestyle-related diseases and associated health problems have increased. To deal with such problems, a balanced lifestyle through physical exercise is highly important. Therefore, much focus has been placed on wearable activity measuring devices such as pedometers to monitor peoples physical activities. Such devices digitize and continuously monitor various daily physical activities. Wearable devices can also be used for performance improvement in sports. People practice sports in order to become better; thus, quantitatively understanding the change in performance is paramount for sports training as it could help discover the evolution of ones physiological and physical performance. Presently, however, in many situations, only physical performances of the athletes are measured and physiological performances are entirely ignored. Along with the widespread use of wearable sensor devices, research and techniques for analyzing the movement of bodies and tools from acquired data are progressing in sports fields and the like by attaching sensors to the body and gears.

*This work was not supported by any organization

[1]G. Lopez, S. Abe, K. Hashimoto and A. Yokokubo are with College of Science and Engineering, Department of Integrated Information Technology, Aoyama Gakuin University, Sagamihara, Japan `guillaume at it.aoyama.ac.jp`

In the field of skills science, there are some research works consisting in attaching a sensor to a tennis racket and analyze its behavior[1], and others focusing on the estimation of baseball pitching speed using a wrist-mounted acceleration sensor and laser apparatus[2]. However, in addition to requiring dedicated sensors that require computer post-processing, there is no feedback to improve skills on-site. Therefore, in this research, we propose a sports skill improvement support system that can be used in daily life. It is using a smartwatch, which is more and more popular as a wrist-worn type sensor, to evaluate and feedback skill level in real-time. In this paper, we present the design of the proposed system and report the investigation results about its effectiveness for individual sports skills.

II. STATE-OF-THE-ART

Up to now, many researches have proposed to evaluate quantitatively sports skills. For long time, they have been principally carried-out based on three-dimensional image analysis, whether it is for baseball [3], [4], [5], [6], [7], [8], tennis [9], [10], [11], [13]. Through these studies, joint motions of shoulder, elbow, forearm, wrist, and fingers during pitching have been kinematically explained, and dynamic analysis also attempted. However, three-dimensional image analysis is disadvantageous for processing a large number of subjects or multiple attempts since the measurement and the analysis become complex and clumsy. On the other hand, thanks to the down-sizing of micro-machines, measurement using tiny sensors attached to the body or the gear is advantageous in that immediate processing and a large amount of data processing are possible. Recently, several studies dedicated to arm movement have been undertaken in Tennis and Baseball.

In their extensive review of technologies available for tennis serve evaluation, Tubez et al. raise the great prospect offered by markerless systems based on inertial measurement units for real situation evaluation [12]. The serve has been described as the most important stroke in tennis [14], [15]. The serve is also the easiest stroke to analyze in tennis because it is a closed skill. These are the major reasons why a large number of studies have focused on this stroke for many years. Ahmadi et al. used two inertial gyroscope sensors to measure the upper arm internal rotation during the first serve [16], [17]. They observed similar tendencies as those obtained from a marker-based motion capture method for shoulder rotation acquisition and concluded that gyroscopes could be used for tennis serve evaluation. Sato et al. attempted to elucidate the behavior of the tennis racket

978-1-5386-9151-9/19/$31.00 ©2019 IEEE

at the flat serve, slice serve, and spin serve by measuring the angular velocity just before the impact of serve with a triaxial acceleration sensor mounted on the grip end of the racket [18]. By comparing time series change pattern of each serve, the difference of angle and moving direction of the impact face was clarified. Masuda et al. proposed a system that can give afterward advice about ball strike by analyzing the data measured by four sensors attached to the head, upper arm, waist, and pivot foot[1]. Analytical items of the form are following five items: shake-off, rotation of waist, swing speed, footrest, ball gaze. However, this system requires a computer to analyze the data of the sensors, and it is necessary to go check the computer display each time after the swing. Blank et al. recently studied the classification of Table Tennis strokes using a racket instrumented with accelerometer and gyroscope to capture the movement of the wrist and the rotation of the racket[19]. However, the user has to have an instrumented racket to play Table Tennis.

More recently, Huy Vu et al. explored the possibility of using a smartwatch to accurately track the hand movement and gestures during table tennis [20]. They developed a new approach composed of a HMM-based gesture recognition framework that does not need an explicit segmentation step, and a per-gesture trajectory tracking solution that tracks the hand movement only during these predefined gestures. Though their approach works efficiently if calibrated for each user (the precision is 87% and the recall is 92%), it performs poorly with a general model (the precision is about 50% and the recall is about 70%). Furthermore, targeted application being video games, proposed approach, though working in real-time with a computer or game machine, cannot be implemented on board of a smartwatch (HMM is not programmable and computation will be too slow).

In baseball also, many studies have been carried out to analyze pitchers arm motion. Saito et al. placed three acceleration sensors on the wrist, from which data they pattern classified acceleration waveforms before and after release during the throwing motion. Further, they used a laser device to estimate the ball speed[2][21].They also investigated the relationship between the peak value of the upper limb and trunk angular velocity and the ball speed[22]. Although the angular velocity of the upper arm and the inner angle of the shoulder due to the arm swing were strongly correlated with the ball speed, the correlation between the angular velocity and the angular velocity of the forearm with the ball speed were reported to be low.

On the other hand, practical personal services for racket sports strike quantification have been started-up recently. In the last few years, manufacturers have proposed easy to use wearable coaching devices for the general public. These devices are integrated to the baseball ball ("Strike" by Jingle Tech Co., Ltd.[23]), or externally attached to the racket ("Smart Tennis Sensor" by Sony Corporation [24]) or the wrist ("Babolat Play" by Babolat [25]). These systems make racket smart and provide information (e.g. number of most common type of stroke) and measure specific characteristics of the game and strokes (e.g. power, speed, impact location in the racket, ball spin, number of shots, energy cost or play time). With these, it became possible to check the swing speed and the number of revolutions of the ball, but neither has the function to provide feedback for skill improvement. Also, since the device is expensive and dedicated to a single sport, there is still a big barrier to easy and widespread utilization.

As mentioned above, although there is research on behavioral motion analysis by wearable sensors in the sports field, in many cases, feedback on operation cannot be returned in real time or special sensors are required, lacking convenience. Therefore, in this research, we proposed an on-site personal sports skill improvement support system using only a smartwatch to measure and feedback immediately arm motion behavior.

III. OUTLINE OF PROPOSED SYSTEM

As it has been reported in past studies about pitching behavior, the deceleration of wrist before ball release is a frequent phenomenon that has an important effect on ball throwing speed[26], [6]. Also, in tennis, works based on inertial sensors, such as "Babolat Play" ([25]), equipment placement on the wrist is a common point. Hence, in this research, we propose a system using a smartwatch to measure directly wrist velocity and acceleration. Concretely, we developed an application on SONY's SmartWatch 3 SWR 50 ("smartwatch") as a versatile wearable device for applications (Fig.1).

Fig. 1. SONY's SmartWatch3 SWR50 (quoted from [9])

With the proposed system, we carried out both technical evaluation and learning assistance efficiency by acquiring data from sensors embedded in the smartwatch attached to the dominant hand of the player and analyzing behavior difference induced by the real-time feedback. Until now, it was only possible to judge whether some movement was done with the correct form by our own sense, coach's guidance, video, etc. However, by using this system, it becomes possible to get information about the form by checking right after the end of the movement the watch screen where some feedback based on actual data can be provided. Moreover, it is possible to simultaneously perform data collection from embedded sensors, motion analysis on-board, and visual feedback presentation with one single device, that is even without pairing it with a smartphone. Such, the user does not need to take time and effort to carry another device, nor he needs to take it out or go to check some machine to get some feedback. Therefore he can practice more effectively.

Since the purpose of the proposed system is to help users improve their skills, we have implemented a function to verify whether movements are performed in the correct form and provide some feedback. The numerical criterion used when evaluating skills are based on the movement form judgment method described in the next section. Also, to demonstrate the versatility of application, we developed application software (from now on referred to as "app.") targeting following two disciplines/actions: baseball pitching action (focusing on the ball speed) and tennis serve action (focusing on pronation motion). Figures 2 and 3 show examples of the screens of the two developed applications.

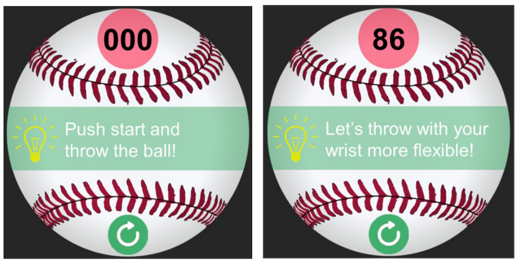

Fig. 2. Screenshots of the developed app. for pitching speed and form improvement support: start (left), and feedback (right) screens

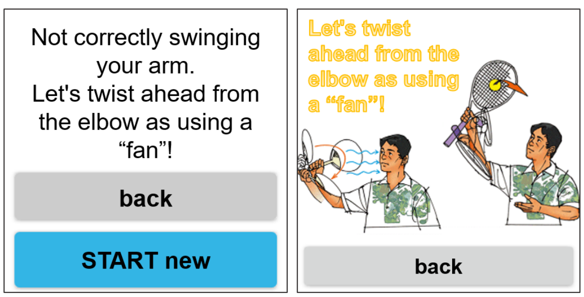

Fig. 3. Screenshot of the developed app. for tennis serve form improvement support: text feedback (left), and image feedback (right) screens

IV. Evaluation of Movement State Estimation Methods

To be sure to acquire enough information on the movement of the arm necessary for constructing the system, we first analyzed the motion using a compact and high-performance motion sensor. In this experiment, we use the inertial motion unit (IMU) IMU-Z2, which is a nine axes (3 axes acceleration 3 axes angular velocity 3 axes geomagnetism) wireless motion sensor from ZMP Inc. (https://www.zmp.co.jp/) (Fig.4 left). IMU-Z2 minimum sampling interval is 1msec for acceleration and 3msec for angular velocity. Sensors sensitivity was set respectively to $\pm$4G (12bits) and $\pm$500 deg/s (16bits) When measuring, the IMU-Z2 was installed on the wrist of the dominant hand. Data obtained from the IMU-Z2 were sent to a PC via Bluetooth (wireless), and logs were output using the standard development software provided by ZMP Inc.

The definition of the angular velocity vector at the time of mounting the sensor is as shown in Figure 4 right. In this research, in order to verify with basic movement, we measured only overthrowing in baseball pitching motion and flat serving in tennis serving motion.

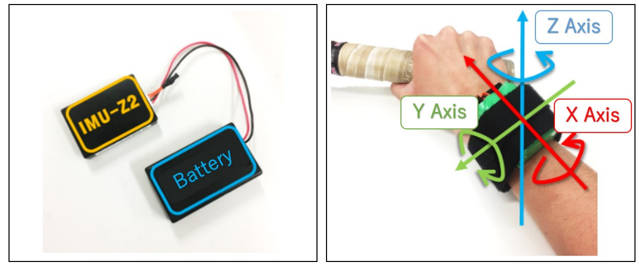

Fig. 4. IMU-Z (left) and the angular velocity vector at the time of installation (right)

A. Measurement of baseball pitching motion

In order to estimate the ball speed, we collected a total of 124 data samples of ball speed and wrist angular velocity during the pitching movement, simultaneously measured from six male subjects in their twenties. For the measurement of the actual ball speed, a speed gun (Speed Star V manufactured by Hanshin Trading co., Ltd.) was used. Within the three axes coordinates as shown in Figure 4 (right), the maximum value of each axis angular velocity were extracted and converted into linear speed (referred to as a pitching arm speed) according formula (1). In formula (1), v_a is the pitching arm speed in km/h, θ the throwing arm wrist angular velocity in m/s, and r the radius in meters of the circumference of the trajectory that the throwing arm draws at the time of pitching. The average diameter of the circumference of the orbit from the swinging up of the arm to the swinging down was about 1m, so r has been defined as 0.5m in this study. A scatter diagram of pitching arm speed and actual ball speed was plot and the correlation was examined (Fig.5).

$$v_a = (\theta * 2\pi * r) * 3.6 \tag{1}$$

TABLE I
Correlation between ball velocity and maximum arm rotation speed, and between ball velocity and maximum arm linear acceleration, according each axes

Axis	Correlation (rotation velocity)	Correlation (linear acceleration)
x	-0.16	0.6
y	0.74	-0.15
z	0.69	-0.64

As shown in Table I, a strong positive correlation was found between the ball speed and the pitching arm speed obtained from the Y axis angular velocity of the wrist. Next, three approximation formulas were created from the scatter plot of the Y axis angular velocity where the strong correlation was observed: a linear equation, a quadratic equation, and a cubic equation. In the three regression

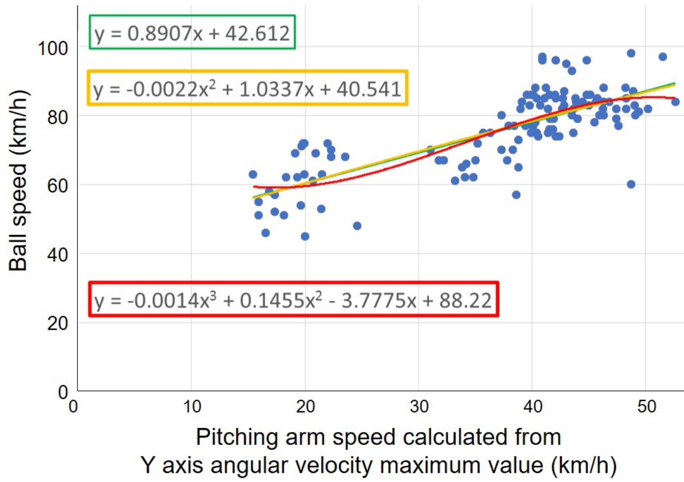

Fig. 5. Scatter plot of throwing arm speed and ball speed, with three regression patterns

formulas thus created, we investigated which one had the highest ball speed estimation accuracy. For that purpose we had three of former subjects throwing six balls each, and compared the ball speed measured with a speed gun and the estimated ball speed. Table II shows the estimation accuracy and standard deviation of each regression formula. Here, the accuracy value is calculated as the percentage the estimated ball velocity falls within the range of ±10 km/h the value measured by the speed gun. The highest accuracy (83%) and the lowest standard deviation ($10\,\mathrm{km/h}$) were obtained when using the quadratic approximation formula. Based on the above results, we selected the quadratic approximation formula (2), where v_b is the estimated ball speed, and v_a the linear arm speed. Such, we can estimate ball speed from Y axis angular velocity data on the smartwatch.

$$v_b = -0.002 * v_a^2 + 1.03 * v_a + 40.5 \tag{2}$$

TABLE II

BALL SPEED ESTIMATION ACCURACY AND STANDARD DEVIATION OF EACH APPROXIMATE EXPRESSION

Equation order	Accuracy	Standard deviation
1^{st}	50%	10.1 km/h
2^{nd}	83%	9.9 km/h
3^{rd}	33%	10.3 km/h

B. Measurement of tennis serve motion

In addition to the serve's swing speed and twist of the arm, it is said that pronation, which is a movement that combines in-ward and inner rotation, is important. The in-ward rotation refers to the twisting motion of the forearm, and the inner rotation refers to the movement of twisting the upper arm. The inner elbow rotates the part ahead of the elbow sharply, accelerates the swing, and produces a sharp rotation of the racket head due to the rotation. Therefore, we verified whether the three serve characteristics of pronation, swing speed, and arm twist can be automatically detected from smartwatch embedded sensors signal.

Regarding the determination of the swing speed, it is sufficient to examine the magnitude of the inner rotation of the shoulder at the time of swing, and its magnitude can be judged from values of Y axis angular velocity and Z axis angular velocity of the forearm. Regarding the judgment of arm twist, it suffices to investigate the magnitude of in-ward motions of the forearm, which can be judged from the value of the X axis angular velocity. Concerning the pronation motion, since it is a high level technique, we decided to judge not its magnitude, but only whether it is performed or not, to be able to observe a clear difference between novice and expert users.

In order to discriminate the presence or not of pronation motion, we asked two subjects who had more than 10 years of tennis practice experience, to perform five flat serves with the pronation motion and five flat serves without pronation motion. Figure 6 shows one characteristic sample of angular velocity data for one subject with (top) and without (bottom) pronation motion. First, the ball impact was judged by comparing the video recorded at the time of measurement with the angular velocity data. It could be observed that the ball impact timing corresponds to the maximum value of the X axis angular velocity, both with and without pronation motion.

Next, we compared the angular velocity data of Flat serve with and without pronation motion. Though X axis angular velocity is correlated to forearm twist, its value reaches a positive peak at both with or without pronation motion, and just the magnitude differs. However, focusing attention on the Z axis angular velocity, it could be observed that it reaches a positive peak just after the ball impact when pronation motion is performed, while it is not the case when pronation motion is not performed (Fig. 6). Indeed, the serve with pronation motion is a serve where the racket face returns 180 degrees after the impact, the front arm is twisted at that time, so the rotation of the Z axis changes from the rotation in the ”minus” direction to the rotation in the ”plus” direction. Such, it was decided to determine the use of pronation motion by checking the maximum value of the Z axis angular velocity (Z_{MAX}) after the impact. Table III sums-up the signal features and methods used to evaluate the three serve characteristics focused in this study.

TABLE III

DESCRIPTION OF WHICH SENSOR SIGNAL FEATURES USED TO EVALUATE THE THREE SERVE CHARACTERISTICS: SWING SPEED, PRONATION MOTION, AND ARM TWIST MOTION

swing speed	largest magnitude among the absolute values of Y and Z axes angular velocity of the forearm
arm twist motion	maximal magnitude of the X axis angular velocity
pronation motion	performed if magnitude of the Z axis angular velocity following ball impact is positive

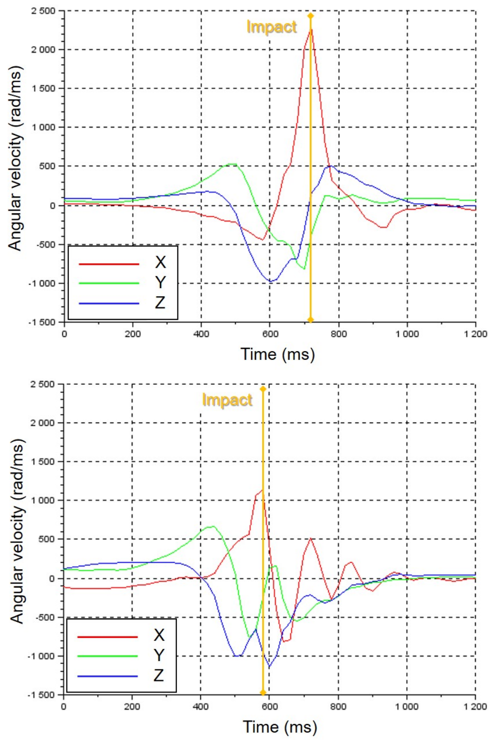

Fig. 6. Angular velocity data of Subject A: with pronation motion (top), without pronation motion (bottom)

V. Use evaluation of each support system

We verified the effectiveness of both skill improvement support apps from both the quantitative improvement of the movements and the subjective improvement issued from questionnaire after having the user actually use the proposed system. In this experiment, Wilcoxon's signed rank sum test has been used when examining the significance of differences between representative values of each group of samples because the number of samples was small and it was not clear whether it follows the normal distribution or not. Models described in previous sections have been defined based on high-end sensor (high sampling rate and sensitivity). However the sampling rate of the smartwatch is not guaranteed and limited to about 120Hz, and its sensitivity limited, such developed models may not be translated accurately. Effectively, pitching motion and serve motion are very intense movements, and in the smartwatch used in this research, it exceeded the maximum value that can be obtained by the embedded acceleration sensor. Since no such value saturation occurred with the embedded gyroscope, and angular velocity signal reveal valuable for both pitching speed estimation and serve form characterization, the models based on gyroscope data has been used for implementation in the smartwatch app.

A. Baseball Pitching Behavior

1) Experimental outline: For 13 subjects, we examined whether there is a significant difference between the average ball speed and the maximum ball speed in both cases of using or not developed smartwatch app. In each case, the subjects threw the ball 10 times at full power. Using or not developed app was performed randomly to avoid the order effect. In addition to ball speed, based on estimated speed and accelerometer signal, six types of advice were displayed according to the conditions as described in Table IV. Advice 1 to 3 are based on sensor signal, while advice 4 to 6 are based on experience. In addition to the quantitative evaluation using exact ball speed data collected simultaneously from the speed gun, subjective assessment was collected from the subjects to evaluate both proposed system and whether each feedback advice were adequate or not.

TABLE IV
PITCHING FORM ADVISES AND THERE SELECTION CONDITIONS

Feedback advice	Selection conditions
[1]Lets shake off your arm!	when x axis acceleration minimum value is higher than $-2m/s^2$
[2]Lets throw swinging down from the top!	when z axis acceleration maximum value is lower than $10m/s^2$ and previous condition not satisfied
[3]Lets step your foot a little bit further!	when estimated ball speed is higher than $80km/h$ and previous conditions not satisfied
[4]Lets throw with your wrist more flexible!	when above conditions are not satisfied
[5]Let's put the power on your fingertips at the moment of throwing!	when feedback [4] is displayed 5 times consecutively
[6]Keep on like this!	when estimated ball speed is higher than $100km/h$

2) Quantitative Evaluation: First, when verifying the accuracy of ball speed estimation using the smartwatch, the estimation accuracy was 78% in the range of $\pm 10\,\mathrm{km/h}$, and the standard deviation was $6\,\mathrm{km/h}$. Although the precision was lower than the estimation using the IMU-Z2 performed in the preliminary experiment, the value of the standard deviation became smaller (83%, sd $10\,\mathrm{km/h}$). As a result of the Wilcoxon signed rank sum test, both the average ball speed and the maximum ball speed were significantly higher when subjects used developed app (Fig. 7). This difference was observed for all subjects. From this, it is thought that giving feedback after each pitch may help in some way to grasp the point of pitching motion, leading to a more stable form and consequently throwing faster balls more stably.

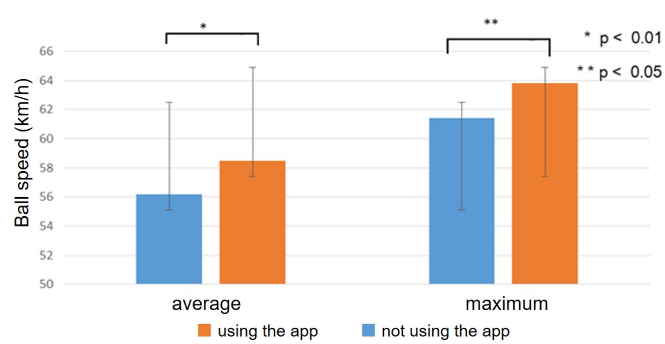

Fig. 7. Ball pitching motion evaluation results

3) Subjective Evaluation: Figure 8 shows the results. From the answer to "Are you eager to know your pitching speed?", it can be said that by simply measuring the ball speed easily may increase the motivation for playing catch ball. Also, though smartwatch display is tiny, feedback display design was easy to see for the majority of the subjects. On the other hand, it was surprising that almost half of the subjects were bothered by wearing the device, even if it is just a wristwatch. Even so, all the subjects felt eager to improve their pitching form thanks to the on-site feedback. The advice provided about the pitching form, though just approximative at this stage of the study, were in adequation with the feelings of the user. However, most subjects could not overcome the thresholds set for advice 1 to 3 such these pieces of advice were not displayed. Further study of pitching form quantitative evaluation is necessary.

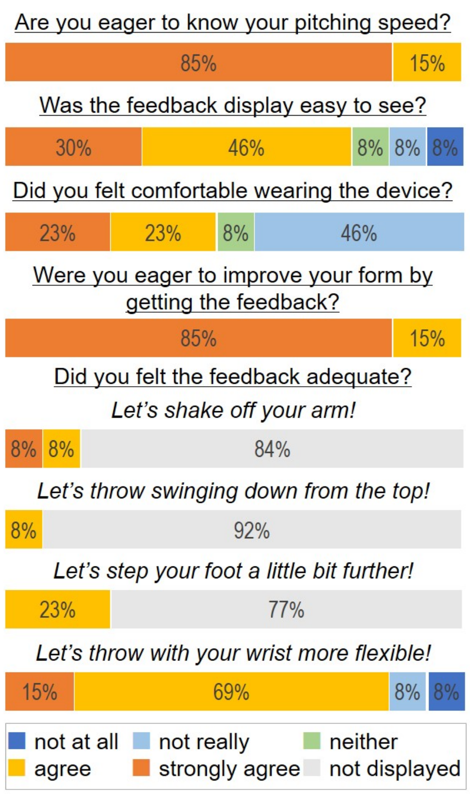

Fig. 8. Results of subjective assessment about using developed pitching feedback system

B. Serve behavior of tennis

1) Quantitative Evaluation: We asked eight subjects to wear a smartwatch and serve 10 times in both two following conditions: using developed app and getting feedback after serving and not using the app (so without feedback). Using or not developed app was performed randomly to avoid the order effect. In order to avoid as much as possible difference in force among the 10 balls, it was instructed to the subjects to serve with the best effort for every ball. The angular velocity data due to the serve motion were logged for further analysis afterwards. In both cases where feedback was given and where it was not given, the average value of Z_{MAX} (maximum value of Z-axis angular velocity), average value of X_{MAX} (maximum value of X-axis angular velocity), and average value of swing speed were compared. As a result of the Wilcoxon signed rank sum test, there was a tendency that Z_{MAX} average value and the X_{MAX} average value were significantly higher in app feedback condition. Z_{MAX} is a value to judge whether the pronation operation is correct, such the result can be interpreted such improvement of the pronation motion ability was observed in all the subjects by using the smartwatch feedback app. Since X_{MAX} is a value corresponding to the inboard motion of the forearm, the result can be interpreted such using the smartwatch feedback app enables to improve the magnitude (power) of inboard motion. Concerning swing speed, there were no significant difference. However, since the average swing speed was higher for the majority of the subjects when using the app, it is possible that the feedback itself was not meaningless, but rather the explanation was inadequate for specific subjects.The verification results are shown in Fig. 9.

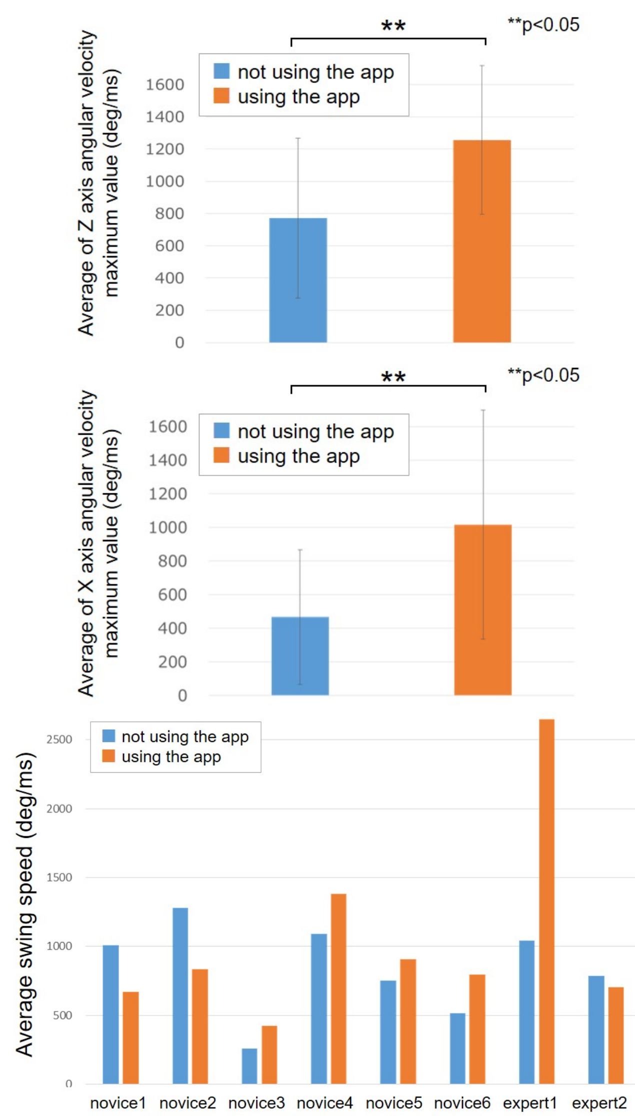

Fig. 9. Serve motion evaluation result: average Z_{MAX} (top) and average X_{MAX} (middle) off all subjects, and difference in average swing speed value for each subjects (bottom), whether using or not developed app

VI. CONCLUSION

In this research, we proposed "a system for improving individual sports skills on site" that can confirm feedback immediately after operation using only smartwatch. We analyzed the ball speed estimation method for quantifying pitching motion of baseball using a high performance motion sensor and the method of judgment of important podium motion by serve motion of tennis. Based on the result, we implemented a smartwatch application that can determine the action in real time. As a result of verifying the effectiveness of the support system provided by the developed application, the average ball speed and the maximum ball speed of all the subjects in pitching have improved, and the improvement of the pronation movement in serve was also seen.

This time, proposed skill support function has been applied to baseball pitching motion and tennis' serve motion, but since smartwatch is a device that can be used in everyday life, we believe it can be sufficiently effective as individual skill improvement support system in any sports where arm movement is greatly related to skill. Some little accuracy decrease of the original models have been observed due to smartwatch's limited sensing capabilities (sampling rate, sensitivity). However, development of new algorithms, as well as addition of up-sampling and interpolation pre-processing could help deal with these issues. Moreover, we can expect the sensitivity and sampling rate of the sensors embedded into the smartwatch keeps improving in future device's versions, such it can be expected that the proposed system will be more accurate. Besides, although the smartwatch was tightly attached, its alignment with the wrist could affect the results since it causes a slight displacement of the angular velocities axes. A calibration step would overcome this issue. However, we believe that the necessity to calibrate frequently is not convenient for the users and will reduce greatly the usability of proposed system. In the system developed in this research, we think that improvement is necessary concerning the following three points.

- Improving ball speed estimation accuracy
- Increasing the variety of feedback
- Verifying the validity of each feedback

REFERENCES

[1] D. Masuda, K. Tasaka, T. Ohgishi and, S. Obana, "Proposal of Progress Assist System for Tennis using Wearable Sensors," in Proc. of Multimedia, Distributed, Cooperative and Mobile Symposium (DICOMO'2014), IPSJ Symposium Series 2014:545-52 (06/2014). [in Japanese]

[2] K. Saitou, Y. Ohgi, S. Inoue, H. Ichikawa, M. Yamagishi, C. Miyaji, S. Takai, Estimation of Ball Speed in Baseball Pitching from Acceleration Measured at the Wrist, Japan J. Phys. Educ. Hlth. Sport Sci. 47:41-51 (01/2002). [in Japanese]

[3] M. Feltner and J. Dapena, "Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch," Int. J. Sport Biomech. 2:235259 (1986).

[4] C.J. Dillman ,G.S. Fleisig and J.R. Andrews, "Biomechanics of pitching with emphasis upon shoulder kinematics," J. Orthop. Sport Phys, Therapy 18:402-408 (1993).

[5] S.L. Werner, G.S. Fleisig, C.J. Dillman, and J.R. Andrews, "Biomechanics of the elbow during baseball pitching," J. OrthoP. Sport Phys. Therapy 17:274-278 (1993).

[6] Wang.Y.T., H.T. Ford III, H.T. Ford Jr, and D.M. Shin, "Three-dimensienal kinematic analysis of baseball pitching in acceleration phase," PerceptMotor Skill 80:43-48 (1995).

[7] S.W. Barrentine, T. Matsuo, R.F. Escamilla, G.S. Fleisig and J.R. Andrews, "Kinematic analysis of the wrist and forearm during baseball pitching," J. Appl. Biomech. 14:24-39 (1998).

[8] T. Matsuo,Y. Takada, T. Matsumoto, and K. Saitou, "Biomechanical characteristics of sidearm and underhand baseball pitching: Comparison with those of overhand and three quarterhand pitching," Jpn. J. of Biomechanics in Sports and Exercise 4:243252 (2001).

[9] Emmen, H., Wesseling, L., Bootsma, R., Whiting, H., and van Wieringen, P., "The effect of video-modelling and video-feedback on the learning of the tennis service by novices," Journal of Sports Sciences 3(2):127138 (1985).

[10] Chow JW, Carlton LG, Lim YT, Chae WS, Shim JH, Kuenster AF, Kokubun K., "Comparing the pre- and post-impact ball and racket kinematics of elite tennis players' first and second serves: a preliminary study," J Sports Sci. 21(7):529-37 (07/2003).

[11] C-C Chaiang,Y-H Nien,J-Y Chiang and T-Y Shiang.,"Kinematic Analysis of Upper Extremity in Tennis Flat and Topspin Serve," Journal of Biomechanics 40(2) (12/2007).

[12] F. Tubez, C. Schwartz, J. Paulus, J.L. Croisier, O. Brüls, V. Denoël, B. Forthomme, "Which tool for a tennis serve evaluation? A review," Int. J. of Performance Analysis in Sport (01/2018). doi:10.1080/24748668.2017.1419407

[13] R. Razali, "The effect of direct video feedback on performance of tennis serve," in Proc. of the 30th Annual Conference of Biomechanics in Sports, pp.241244 (2012).

[14] Kibler, B., "The kinetic chain in tennis: Do you push or pull?," Aspetar Sports Medicine Journal 1(1):4043 (2012).

[15] Whiteside, D., Elliott, B., Lay, B., and Reid, M., "A kinematic comparison of successful and unsuccessful tennis serves across the elite development pathway," Human Movement Science 32(4):822835 (2013).

[16] A. Ahmadi, D. Rowlands, D. James, "Towards a Wearable Device for Skill Assessment and Skill Acquisition of a Tennis Player During the First Serve," Sports Technology 2(3-4):129-36 (2009).

[17] A. Ahmadi, D. Rowlands, D. James, "Development of inertial and novel marker-based techniques and analysis for upper arm rotational velocity measurements in tennis," Sports Engineering 12(4):179188 (2010).

[18] B. Sato, A kinematic analysis of tennis racket during different types of service, Waseda Univesity Graduate School of Sport Sciences, Master Thesis 2009. [in Japanese]

[19] P. Blank, J. Hoßbach, D. Schuldhaus, and BM Eskofier, "Sensor-based stroke detection and stroke type classification in table tennis," in Proc. ACM Int. Symposium on Wearable Computers, 93100 (2015).

[20] TH. Vu, A. Misra, Q. Roy, K. Choo Tsu Wei, Y. Lee, "Smartwatch-based Early Gesture Detection and Trajectory Tracking for Interactive Gesture-Driven Applications," in Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 2(1):1-27 Article 39 (03/2018).

[21] K. Saitou, S. Hosoya, S. Inoue, H. Yukawa, "Effects of breaking ball on the states of ball-release and the motion during baseball pitch," in proc. of JSME Symposium on Sports and Human Dynamics 2013 (11/2013). [in Japanese]

[22] K. Saitou, K. Inoue, S. Inoue, M. Watanabe, J. Sakai, T. Takeda, Measurement of motion of upper limb and trunk with inertial sensors during baseball pitch," Journal of Nagoya Gakuin University Humanities and natural sciences 48(1):33-48 (07/2011). [in Japanese]

[23] JingleTek Corp., Strike (https://www.makuake.com/project/strike/).

[24] SONY Corp, Smart Tennis Sensor (http://smartsports.sony.net/tennis/JP/ja/).

[25] Babolat, Babolat Play (http://ja.babolatplay.com/play).

[26] A.E. Atwater, "Biomechanics of overarm throwing movements and of throwing injuries," Exerc. Sport ScL Rev. 7:43-85 (1979).

[27] Sony mobile communications Corp., SmartWatch3 SWR50 (http://www.sonymobile.co.jp/product/smartproducts/swr50/).