

## Original Article

# Radial pulse waveform and parameters in different types of athletes

An-Ran Wang<sup>1</sup>, Jun Su<sup>1,2</sup>, Song Zhang<sup>1</sup>, Lin Yang<sup>1</sup>

<sup>1</sup>College of Life Science and Bio-Engineering, Beijing University of Technology, Beijing 100124, China;

<sup>2</sup>Department of Youth Sports, Beijing Municipal Bureau of Sports, Beijing, 100075, China

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**Abstract:** Objective: To classify the sports events by the maximal oxygen uptake ( $\text{MaxO}_2$ ) and the maximal muscular voluntary contraction (MVC) and to collect the radial pulse wave of different sports events and discuss the pulse waveform and characteristic parameters. Patients or other participants: 304 professional athletes were enrolled from Beijing Muxiyuan Sports Technical School. Main outcome measure(s): Normalize each radial pulse waveform and let the waveform cycle and amplitude distribute in the range of 0-100. Analyze the relative time of the maximum point  $T_m$ , the abscissa  $X$  and ordinate  $Y$  of dicrotic notch, the pulse waveform area  $K$  and the pulse wave age index SDPTG. Results: According to the different degree of  $\text{MaxO}_2$  and MVC, the radial descending curves have the distinctive downtrend. The characteristic parameters of  $\text{MaxO}_2$  and MVC groups, such as  $T_m$ ,  $X$ ,  $Y$ ,  $K$  and SDPTG are as well as different. Conclusions: The pulse waveform changing trend of MVC (< 50%) group and MVC (> 50%) group are different while the sports have the same  $\text{MaxO}_2$ . And the pulse waveform changing trend of  $\text{MaxO}_2$  (< 40%) group,  $\text{MaxO}_2$  (40-70%) group and  $\text{MaxO}_2$  (> 70%) group are as well as different while the sports have the same MVC. The various parameters of the most specific group F are the smallest suggests the sports in group F are the most benefit for the cardiovascular.

**Keywords:** Athlete, pulse wave, radial artery, waveform parameter

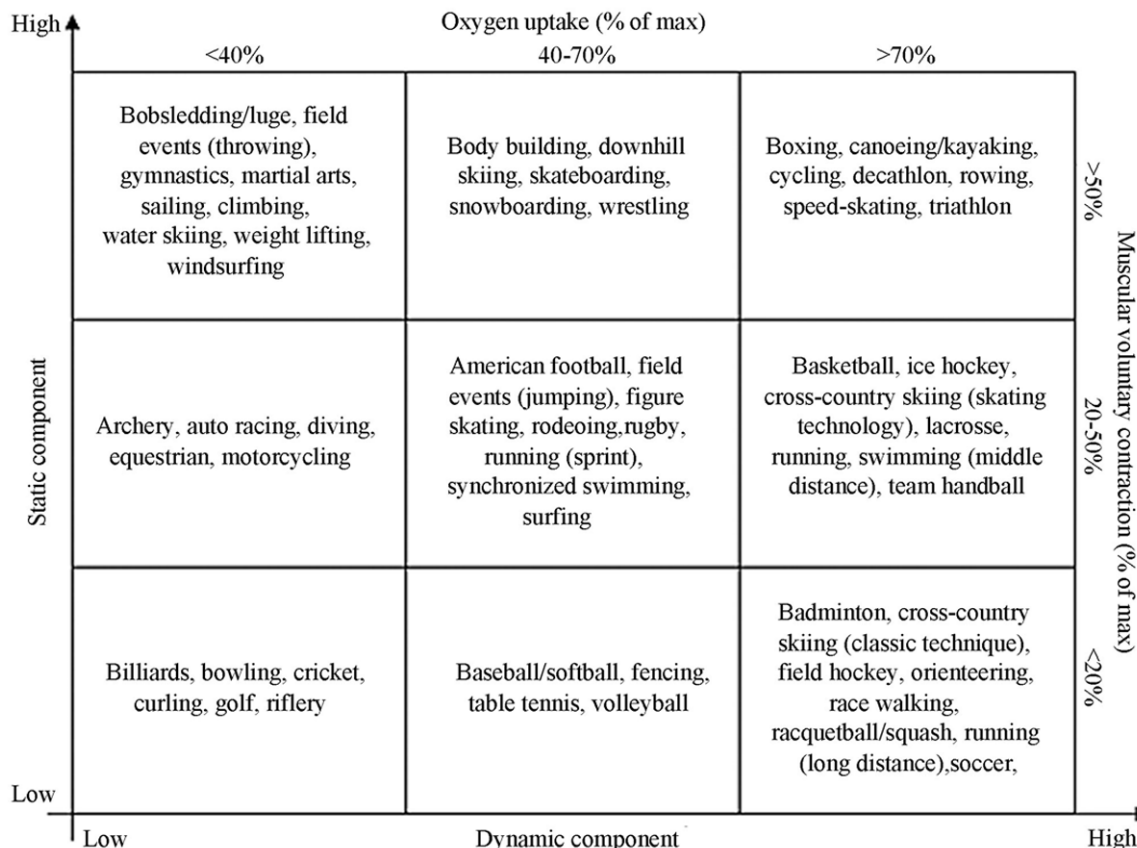
## Introduction

The cardiovascular system is a power organ in human blood circulation. The system is mainly responsible for the body's blood supply and transport. The pulse wave is a reaction of the periodic pressure change, by the blood flow in the arteries that results from the ventricular contraction and diastole. The waveform can reflect the condition of cardiovascular function and blood circulation. And analyze the cardiovascular function with the use of pulse wave detection methods is gradually accepted by the clinical specialists. The study of Weber provided evidence that pulse waveform characteristics can be an important indicator to consistently and independently predict cardiovascular events [1]. Shokawa et al. studied a cohort of 492 Japanese-Americans living in Hawaii during the 10-year follow-up. The research demonstrated that the pulse wave velocity (PWV) could predict cardiovascular disease mortality [2]. Blacher showed that aortic pulse

wave velocity (PWV) constitutes a forceful marker and predictor of cardiovascular risk in hypertensive patients by a series of experiments [3]. And Cruickshank proved that aortic pulse wave velocity (PWV) is a powerful independent predictor of mortality in both diabetes and glucose-tolerance-tested (GTT) population samples [4]. These researches indicate that the pulse wave contains rich cardiovascular physiological and pathological information. Pulse waveform characteristics, such as the shape, the intensity, the velocity and the rhythm are closely bound up with cardiovascular function [5-7].

Chronic physical training may induce morphological and useful functional adaptations, which affects the heart [8]. Morphological modifications are mainly modest and far from pathologic ones. All these adaptations are helpful for sport's performance. Engage in physical exercise can effectively improve cardiovascular function [9, 10], and the physical exercise has

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**Figure 1.** Classification of sports according to dynamic and static exercise components.

been said to be healthy for the heart even in patients with various forms of cardiac disease [11]. Moreover the athlete is a special group. Their cardio-pulmonary function and skeletal muscle metabolism function are superior to the ordinary people. Cardiac function status directly affects the athletic ability, and strong cardiac function is the necessary quality of the athletes. After a chronic systematic training, athletes' resting heart rate is low, and the stroke volume is large. Their myocardium will be in a state of "energy saves" and the heart burden is small. When athletes exercise, they quickly mobilize the cardiac reserve and improve cardiac output to meet the needs of body movement. Regular participation in intensive physical exercise can enhance diastolic filling and facilitate a sustained increase in the cardiac output that is fundamental to athletic excellence. Such cardiac adaptations are collectively referred to as the "Athlete's Heart" [12]. Not only research on athletes' cardiovascular system function has obvious effect for athletes playing of the competitive ability in the game

and their level of exercise to keep, but also studying different types of cardiovascular function change has the very vital significance of physical exercise and cardiovascular health for the general population. Studies have shown that athletic participation has more than doubled in all major demographic groups in recent years; while simultaneously, children and adults with established heart disease desire participation in sports and exercise [13]. This research analyzes the athletes' cardiovascular function from the point of pulse waveforms and parameters analysis by detecting the radial pulse wave of various athletes.

### Materials and methods

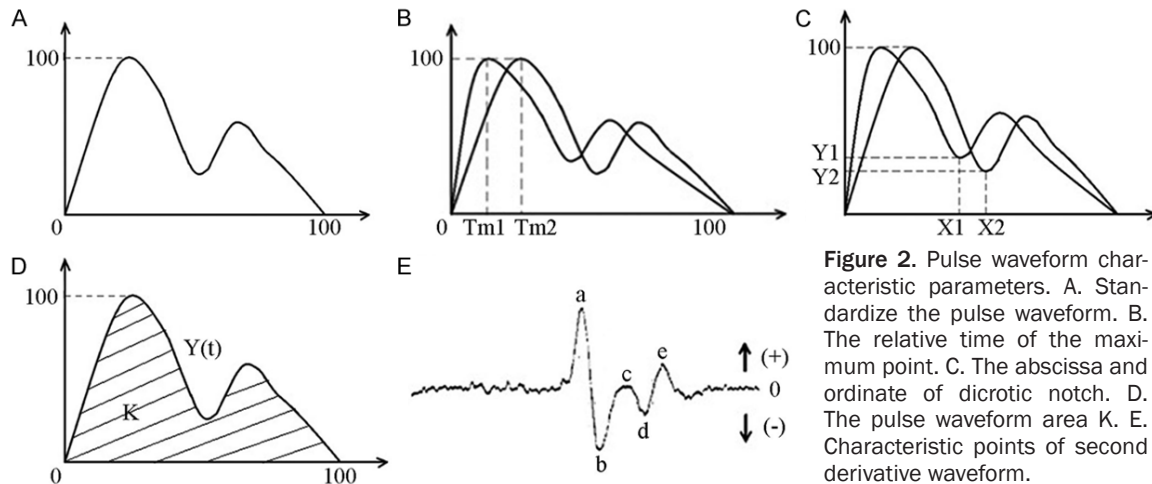
#### Classification of athletes

Sports are classified according to their degree of dynamic and static exercise at the international level. Dynamic exercise, such as distance running, involves changes in muscle length and joint movement with relatively small intramus-

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**Table 1.** Basic information of the subjects

Groups	Group_A	Group_B	Group_C	Group_D	Group_E
Sports	Throwing, gymnastics, martial arts	Wrestling	Boxing, cycling	Archery	Field events (jumping)
N (Sports Detail)	22 (9, 4, 9)	34	34 (19, 15)	10	38
Gender (F/M)	11/11	17/17	17/17	5/5	19/19
Age	20.9±2.1	16.2±1.1	18.8±2.8	19.6±2.4	18.8±2.4
Height	171.3±12.1	166.3±7.1	173.1±6.5	175.8±8.1	179.3±9.9
Weight	74.3±27.7	64.1±9.9	64.4±8.8	71.2±10.9	64.4±12.3



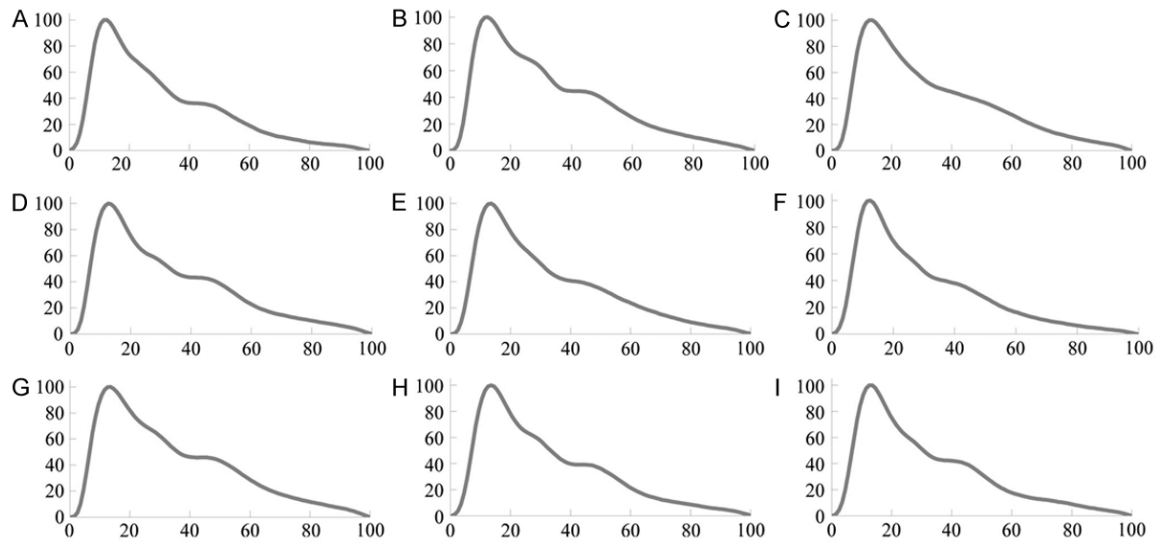
cular force. Conversely, static exercise, such as weight lifting, involves large intramuscular forces with relatively minor change in muscle length and joint movement [14]. This classification scheme considers that each sport has two components: dynamic and static exercise components. Sport can be classified by the level of intensity (low, medium, high) of dynamic and static exercise generally required to perform that sport during competition. The dynamic exercise component is defined in terms of the percent of maximal oxygen uptake ( $MaxO_2$ ) achieved: the intensity of dynamic exercise component is low while  $MaxO_2 < 40\%$ , the intensity of dynamic exercise component is moderate while  $MaxO_2$  is  $40\%-70\%$ , and the intensity of dynamic exercise component is high while  $MaxO_2 > 70\%$ . The static component is related to the percent of maximal voluntary contraction (MVC) reached: the intensity of dynamic exercise component is low while  $MVC < 20\%$ , the intensity of dynamic exercise component is moderate while  $MVC$  is  $20\%-50\%$ , and the intensity of dynamic exercise component is high while  $MVC > 50\%$ . For the convenience of description, we divide the various sports to 9 groups (A-I) according to the classi-

fication standard, as shown in **Figure 1**. This study researches the changes of radial pulse waveforms and parameters in different groups of athletes. Radial pulse waveforms and relevant information of 304 athletes who are training more than 3 years was detected and collected. The basic information of the various groups of athletes is shown in **Table 1**. This study was conducted in accordance with the declaration of Helsinki. This study was conducted with approval from the Ethics Committee of Beijing University of Technology. Written informed consent was obtained from all participants.

### Detecting process

Subjects were asked to sit quietly for 3 minutes and keep resting state in the whole experiment process. The detection equipment is the PowerLab data collection system (ADInstruments Pty Ltd., PowerLab 8/35, Bella Vista NSW 2153, Australia) and its bundled software LabChart 7 which with 30 Hz digital low-pass filter and 1 KHz sampling frequency. The sensor, which is the strain type radial artery pressure pulse waveform sensor with independent

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**Figure 3.** Standard averaged single radial pulse waveforms of 9 groups.

outside 5 V, power supply accessed to the analog signal input by the coaxial cable. We use the PowerLab data collection system to detect the radial artery of the athletes. The sensor was bundled on the strongest point of the right arm where radial pulse beats, neither too loose to let the sensor slip nor too tight to turn the waveform distortional. The steady radial pulse waveform data of 30 seconds was acquired and saved in the computer.

### *Determination of the characteristic parameters*

*Standardize the pulse waveform:* Pulse wave parameters, such as amplitude and cycle, are different on account of the discrepancy of the subjects. A unified standard quantitative plane has been established in order to compare pulse waveforms and calculate the pulse wave parameters with a uniform method. The maximum of X and Y-axis in this plane are both 100. The amplitude and the cycle of each radial pulse waveform were adjusted (enlarged or shrink) and distributed in the range of 0 to 100. Therefore the data of the pulse waveforms can be standardized, as shown in **Figure 2A**.

*Relative time of the maximum point:* The maximum point is an important pulse waveform characteristic point and it may be different with the sundry pulse waveforms. The pulse waveforms had been placed in the standard quantitative plane, hence, the abscissa value from the starting point to the maximum point is the

relative time of the maximum point  $T_m$ , as shown in **Figure 2B**.

*Coordinates of dicrotic notch:* The dicrotic notch is another important pulse waveform characteristic point and it also may be different with the sundry pulse wave. In this study, the abscissa X and ordinate Y of the dicrotic notch are recorded, as shown in **Figure 2C**.

*Pulse waveform area K:* The waveform parameter K extracted from the area under the pulse waveform can describe the pulse wave general characteristics on the macroscopic angle [15]. The value of K which is the integral area under the pulse waveform curve is defined as:

$$K = \frac{1}{10000} \int_0^{100} Y(t), \text{ as shown in Figure 2D.}$$

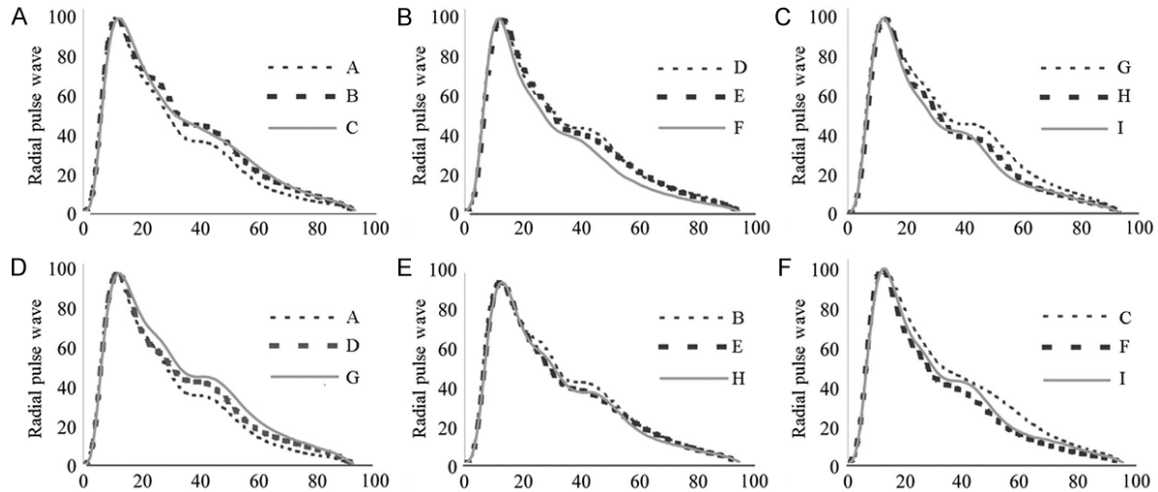
*Pulse wave age index:* Takazawa et al. analyzed the second derivative graph of the pulse waveform and presented five special points (a b c d and e) on the graph, as shown in **Figure 2E**. They demonstrated that different physiological groups would have different second derivative graphs and the amplitude ratio of various points b/a, c/a, d/a and e/a had a good correlation with the age as well as proposed the pulse wave age index SDPTG [16].

## **Results**

### *Radial pulse waveforms*

Steady radial pulse wave data for 30 seconds with the PowerLab data collection system is

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**Figure 4.** Standard averaged single radial pulse waveforms. A: Group A, B and C; B: Group D, E and F; C: Group G, H and I. D: Group A, D and G; E: Group B, E and H; F: Group C, F and I.

**Table 2.** Basic information of the subjects (continues)

Groups	Group_F	Group_G	Group_H	Group_I
Sports	Running, swimming (middle distance)	Riflery	Baseball, table tennis, volleyball	Badminton, field hockey, race walking, racquetball, running (long distance)
N (Sports Detail)	36 (13, 23)	28	38 (1, 23, 14)	64 (11, 8, 16, 6, 23)
Gender (F/M)	18/18	14/14	19/19	32/32
Age	20.1±1.9	18.3±1.9	19.7±5.9	20.4±2.0
Height	175.7±8.4	172.0±9.3	170.2±8.2	173.7±6.4
Weight	64.8±10.5	67.2±17.7	59.9±11.3	61.6±8.1

detected and saved into the computer. Then the data of each subject is averaged to an averaged single pulse waveform according to the number of single pulse wave in the actual measurement. After that, the averaged single radial pulse waveform is standardized and its cycle and amplitude are distributed in the range of 0 to 100. Then the standard averaged single pulse waveforms of subjects are averaged respectively on the basis of groups, namely subjects' of every groups single pulse wave are averaged. The collection of standard averaged single radial pulse waveforms of groups are shown in **Figure 3**. Afterwards the second derivative waveforms based on the standard averaged single radial pulse waveform are calculated to receive the radial acceleration pulse waveforms.

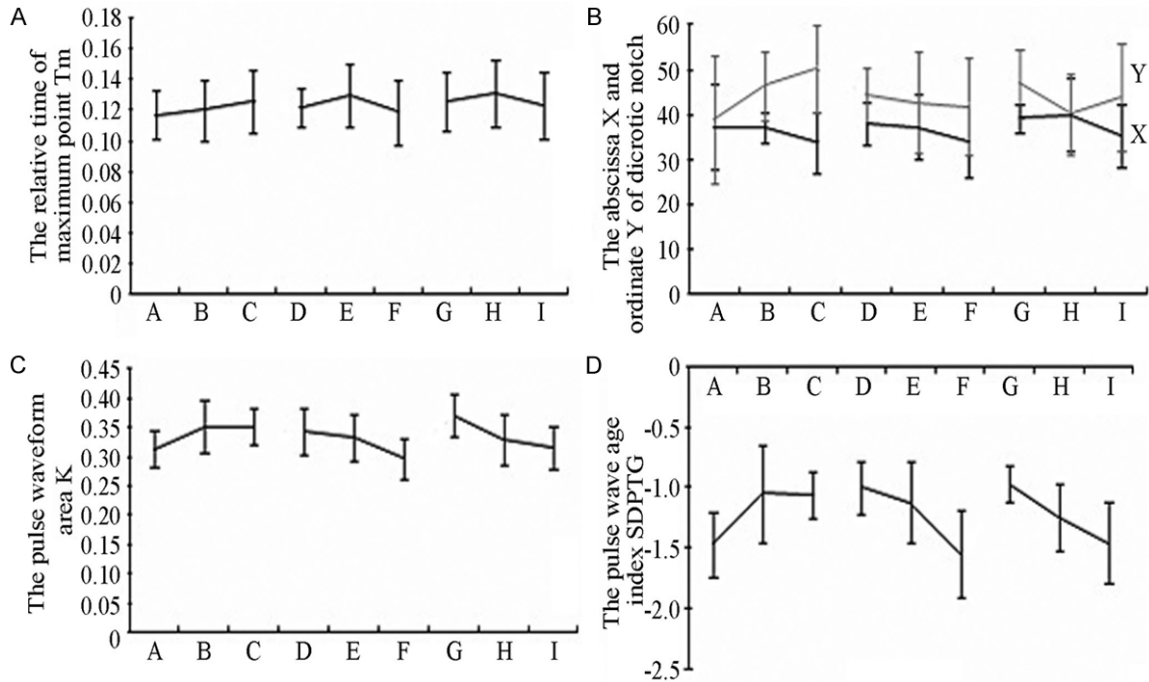
*Pulse waveform parameters trends follow the changing of MaxO<sub>2</sub>*

When MVC > 50%, the radial standard averaged single pulse waveform of different MaxO<sub>2</sub>

groups (Groups A, B and C) are shown in **Figure 4A** and waveform parameters T<sub>m</sub>, X, Y, K and SDPTG of each group are shown in **Table 2**. It is observed that with increasing MaxO<sub>2</sub>, the pulse waveform descending curves (from the maximum point to the end point) gradually move up. The relative time of the maximum point: T<sub>m\_A</sub> < T<sub>m\_B</sub> < T<sub>m\_C</sub>. The coordinates of the dicrotic notch points: X<sub>A</sub> > X<sub>B</sub> > X<sub>C</sub>, Y<sub>A</sub> < Y<sub>B</sub> < Y<sub>C</sub>. The waveform area: K<sub>A</sub> < K<sub>B</sub> < K<sub>C</sub>. The pulse wave age index: SDPTG<sub>B</sub> > SDPTG<sub>C</sub> > SDPTG<sub>A</sub>.

When MVC is 20%-50%, the radial standard averaged single pulse waveform of different MaxO<sub>2</sub> groups (Group D, E and F) are shown in **Figure 4B** and waveform parameters of each group are shown in **Table 2**. It is observed that with increasing MaxO<sub>2</sub>, the pulse waveform descending curves gradually move down. The relative time of the maximum point: T<sub>m\_F</sub> < T<sub>m\_D</sub> < T<sub>m\_E</sub>. The coordinates of the dicrotic notch points: X<sub>D</sub> > X<sub>E</sub> > X<sub>F</sub>, Y<sub>D</sub> > Y<sub>E</sub> > Y<sub>F</sub>.

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**Figure 5.** Pulse waveform parameter changes with the change of  $MaxO_2$ .

The waveform area:  $K_{-D} > K_{-E} > K_{-F}$ . The pulse wave age index:  $SDPTG_{-D} > SDPTG_{-E} > SDPTG_{-F}$ .

When  $MVC < 20\%$ , the radial standard averaged single pulse waveform of different  $MaxO_2$  groups (Groups G, H and I) are shown in **Figure 4C** and waveform parameters each group are shown in **Table 2**. It is observed that with increasing  $MaxO_2$ , the pulse waveform descending curves gradually move down. The relative time of the maximum point:  $Tm_{-I} < Tm_{-G} < Tm_{-H}$ . The coordinates of the dicrotic notch points:  $X_{-I} < X_{-G} < X_{-H}$ ,  $Y_{-H} < Y_{-I} < Y_{-G}$ . The waveform area:  $K_{-G} > K_{-H} > K_{-I}$ . The pulse wave age index:  $SDPTG_{-G} > SDPTG_{-H} > SDPTG_{-I}$ .

We analyzed the changes in the different MVC groups, these led us to find that the lower ( $< 50\%$ ) MVC groups and the higher ( $> 50\%$ ) MVC groups have different changing trend:

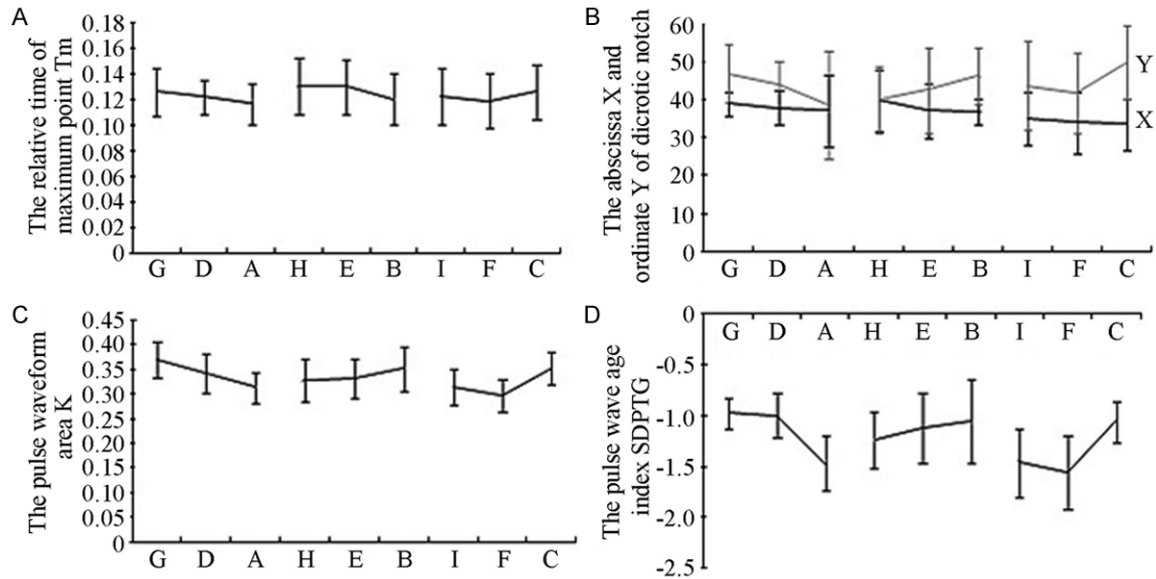
1) With increasing  $MaxO_2$ , the pulse waveform descending curves (from the maximum point to the end) of the lower ( $< 50\%$ ) MVC groups (Groups D, E, F and Groups G, H, I) gradually move down while of the higher ( $> 50\%$ ) MVC groups (Groups A, B and C) move up. 2) As shown in **Figure 5A**, with increasing  $MaxO_2$ , the

maximum points (described by the relative time of the maximum point  $T_m$ ) of the lower ( $< 50\%$ ) MVC groups (Groups D, E, F and Groups G, H, I) first move to the right then to the left while of the higher ( $> 50\%$ ) MVC groups (Groups A, B and C) gradually move to the right. 3) As shown in **Figure 5B**, with increasing  $MaxO_2$ , the dicrotic notch points move to the left generally. The lower ( $< 50\%$ ) MVC groups' dicrotic notch points (Groups D, E, F and Groups G, H, I) move to the lower-left corner while the higher ( $> 50\%$ ) MVC groups' (Groups A, B and C) move to the top-left corner. 4) As shown in **Figure 5C**, with increasing  $MaxO_2$ , the pulse waveform area K of the lower ( $< 50\%$ ) MVC groups (Groups D, E, F and Groups G, H, I) is gradually decreasing while of the higher ( $> 50\%$ ) MVC groups (Groups A, B and C) is increasing. 5) As shown in **Figure 5D**, with increasing  $MaxO_2$ , the pulse wave age index of the lower ( $< 50\%$ ) MVC groups (Groups D, E, F and Groups G, H, I) is gradually decreasing while of the higher ( $> 50\%$ ) MVC groups (Groups A, B and C) are increasing.

*Pulse waveform parameters trends follow the changing of MVC*

When  $MaxO_2 < 40\%$ , the radial standard averaged single pulse waveform of different MVC groups (Groups A, D and G) are shown in **Figure**

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**Figure 6.** Pulse waveform parameter changes with the change of MVC.

**4D** and waveform parameters of each group are shown in **Table 2**. It is observed that with increasing MVC, the pulse waveform descending curves gradually move down. The relative time of the maximum point:  $T_{m\_A} < T_{m\_D} < T_{m\_G}$ . The coordinates of the dicrotic notch points:  $X_{-A} < X_{-D} < X_{-G}$ ,  $Y_{-A} < Y_{-D} < Y_{-G}$ . The waveform area:  $K_{-A} < K_{-D} < K_{-G}$ . The pulse wave age index:  $SDPTG_{-A} < SDPTG_{-D} < SDPTG_{-G}$ .

When  $MaxO_2$  is 40%-70%, the radial standard averaged single pulse waveform of different MVC groups (Groups B, E and H) are shown in **Figure 4E** and waveform parameters of each group are shown in **Table 2**. It is observed that with increasing MVC, the pulse waveform descending curves gradually move up. The relative time of the maximum point:  $T_{m\_B} < T_{m\_E} < T_{m\_H}$ . The coordinates of the dicrotic notch points:  $X_{-B} < X_{-E} < X_{-H}$ ,  $Y_{-B} > Y_{-E} > Y_{-H}$ . The waveform area:  $K_{-B} > K_{-E} > K_{-H}$ . The pulse wave age index:  $SDPTG_{-B} > SDPTG_{-E} > SDPTG_{-H}$ .

When  $MaxO_2 > 70\%$ , the radial standard averaged single pulse waveform of different MVC groups (Groups C, F and I) are shown in **Figure 4F** and waveform parameters of each group are shown in **Table 2**. It is observed that with increasing MVC, the pulse waveform descending curves first move down then move up. The

relative time of the maximum point:  $T_{m\_F} < T_{m\_I} < T_{m\_C}$ . The coordinates of the dicrotic notch points:  $X_{-C} < X_{-F} < X_{-I}$ ,  $Y_{-F} < Y_{-I} < Y_{-C}$ . The waveform area:  $K_{-F} < K_{-I} < K_{-C}$ . The pulse wave age index:  $SDPTG_{-C} > SDPTG_{-I} > SDPTG_{-F}$ .

We also analyzed the changes of the different  $MaxO_2$  groups, these led us to find that the lower (< 40%)  $MaxO_2$  group, the medium (40%-70%)  $MaxO_2$  group and the higher (> 70%)  $MaxO_2$  group have different changing trend: 1) With increasing MVC, the pulse waveform descending curves (from the maximum point to the end) of the lower (< 40%)  $MaxO_2$  group (Groups A, D and G) gradually move down, of the medium (40%-70%)  $MaxO_2$  groups (Groups B, E and H) move up while of the higher (> 70%)  $MaxO_2$  groups (Groups C, F and I) first move down then move up. 2) As shown in **Figure 6A**, with increasing MVC, the maximum points (described by the relative time of the maximum point  $T_m$ ) of lower and medium (< 70%)  $MaxO_2$  groups (Groups A, D, G and Groups B, E, H) gradually move to the left while of the higher (> 70%)  $MaxO_2$  groups (Groups C, F and I) first move to the left then to the right. 3) As shown in **Figure 6B**, with increasing MVC, the dicrotic notch points move to the left generally. The lower (< 40%)  $MaxO_2$  groups' dicrotic notch points (Groups A, D and G) move to the lower-left corner while the medium (40%-70%)  $MaxO_2$

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groups' (Groups B, E and H) move to the top-left corner. 4) As shown in **Figure 6C**, with increasing MVC, the pulse waveform area K of the lower (< 40%) MaxO<sub>2</sub> group (Groups A, D and G) is gradually decreasing, of the medium (40%-70%) MaxO<sub>2</sub> groups (Groups B, E and H) is gradually increasing while of the higher (> 70%) MaxO<sub>2</sub> groups (Groups C, F and I) is first decreasing then increasing. 5) As shown in **Figure 6D**, with increasing MVC, the pulse wave age index of the lower (< 40%) MaxO<sub>2</sub> group (Groups A, D and G) is gradually decreasing, of the medium (40%-70%) MaxO<sub>2</sub> groups (Groups B, E and H) is gradually increasing while of the higher (> 70%) MaxO<sub>2</sub> groups (Groups C, F and I) is first decreasing then increasing.

### Discussion

In this study, we analyzed the athletes' cardiovascular function from the point of pulse waveforms and parameters analysis. The results have shown us that the pulse waveform changing trend of MVC (< 50%) group and MVC (> 50%) group are different while the sports have the same MaxO<sub>2</sub>. And the pulse waveform changing trend of MaxO<sub>2</sub> (< 40%) group, MaxO<sub>2</sub> (40-70%) group and MaxO<sub>2</sub> (> 70%) group are as well as different while the sports have the same MVC.

It is found that the parameters of Group A and Group F are relatively small when studying pulse waveform parameters changing with MaxO<sub>2</sub> or MVC, further, the pulse waveform area K and the pulse wave age index SDPTG of Group F are smaller than Group A. Some researchers have shown that running in Group F is a comprehensive sport and it is the best sport for aerobic exercise. Moreover swimming in Group F is as well as a systemic training. Swimming frequently can enhance the heart function and strengthen the immune system, and the swimming exercise training, without overloading, is an important stimulus for improving the biomechanical parameters and structural properties of the calcaneal tendon [17]. A research demonstrates that swimming training lower the resting blood pressure in individuals with hypertension [18]. Mehrotra's research of different athletes lung function also provides evidence that swimming can most greatly improve the lung function of the athletes compared with football, hockey, volleyball

and basketball [19]. So our research suggests the sports in Group F are the most benefit for the cardiovascular.

Mitchell JH has shown that each sport can be categorized by the level of intensity (low, medium, high) of dynamic or static exercise component, but the bodily collision, the probability of hard impact or the sudden syncopal event can all exert an effect on the athletes [20]. Thus, based on the dynamic and static demands, sports can be classified (**Figure 1**) as Group C (high static, high dynamic), Group E (moderate static, moderate dynamic), Group G (low static, low dynamic), and so forth. High intensity sports may place a rather large burden on the athlete. If an athlete with a cardiovascular abnormality that contraindicates a sport produces a high-pressure load may be advised to avoid sports classified as Group C, and the athlete can work on some moderate sports like Group F. So do researches on the athletes' cardiovascular system function have obvious effect for athletes playing of the competitive ability in the game and their level of exercise to keep. Understand the athlete's cardiovascular characteristics of different types of sports will let us find more reasonable and effective training methods. And it also has the very vital significance of physical exercise and cardiovascular health for the general population.

Radial pulse wave and PPG pulse wave respectively represent the pressure and flow of the blood vessels which the relationship between them constitute the pivotal cardiovascular blood parameters, such as the peripheral resistance and the arterial compliance. We analyzed the pulse waveform and the characteristic parameters of different types of athletes based on the radial pulse wave. Radial pulse wave near the peripheral vascular contains abundant cardiovascular physiology and pathology information. But in actual work, if the radial pulse pressure is the overall pressure pulse of microcirculation, the PPG pulse wave blood flow is the overall volume pulse wave blood flow of microcirculation. The PPG pulse wave contains lots of microcirculation information compared with the radial pulse wave. Improve microcirculation status has important implications for the measure of these diseases; PPG pulse wave is an effective method of observing and evaluating the microcirculation status. So in the future,



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we will research the athletes' cardiovascular function based on the PPG pulse wave.

In summary, it is found that the changes of the lower (< 50%) MVC groups is different from the higher (> 50%) MVC groups while they have the same MaxO<sub>2</sub>, and the changes of the lower (< 40%) MaxO<sub>2</sub> group, the medium (40%-70%) MaxO<sub>2</sub> group and the higher (> 70%) MaxO<sub>2</sub> group is as well as different while they have the same MVC. The pulse waveform area K and the pulse wave age index SDPTG of Group F are smallest, so our research suggests the sports in Group F are the most benefit for the cardiovascular.

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### Disclosure of conflict of interest

None.

**Address correspondence to:** Dr. Lin Yang, College of Life Science and Bio-Engineering, Beijing University of Technology, 100 Pingleyuan, Chaoyang District, Beijing 100124, China. Tel: +86 10 6739 2010; Fax: +86 10 67392010; E-mail: yanglin@bjut.edu.cn

### References

- [1] Weber T, O'Rourke MF, Lassnig E, Porodko M, Ammer M, Rammer M, Eber B. Pulse waveform characteristics predict cardiovascular events and mortality in patients undergoing coronary angiography. *J Hypertens* 2010; 28: 797-805.
- [2] Shokawa T, Imazu M, Yamamoto H, Toyofuku M, Tasaki N, Okimoto T, Yamane K, Kohno N. Pulse wave velocity predicts cardiovascular mortality: findings from the Hawaii-Los Angeles-Hiroshima study. *Circ J* 2005; 69: 259-264.
- [3] Blacher J, Asmar R, Djane S, London GM, Safar ME. Aortic pulse wave velocity as a marker of cardiovascular risk in hypertensive patients. *Hypertension* 1999; 33: 1111-1117.
- [4] Cruickshank K, Riste L, Anderson SG, Wright JS, Dunn G, Gosling RG. Aortic pulse-wave velocity and its relationship to mortality in diabetes and glucose intolerance an integrated index of vascular function. *Circulation* 2002; 106: 2085-2090.
- [5] Westerhof BE, Guelen I, Stok WJ, Wesseling KH, Spaan JA, Westerhof N, Bos WJ, Stergiopulos N. Arterial pressure transfer characteristics: effects of travel time. *Am J Physiol Heart C* 2007; 292: H800-H807.
- [6] Foo JY, Lim CS, Wilson SJ. Photoplethysmographic assessment of hemodynamic variations using pulsatile tissue blood volume. *Angiology* 2008; 59: 745-752.
- [7] Hasegawa S, Sato S, Numano F, Park J, Hoshina S, Endoh H, Suzuki H, Uchiyama M. Characteristic alteration in the second derivative of photoplethysmogram in children. *Pediatr Int* 2011; 53: 154-158.
- [8] Barbier J, Ville N, Kervio G, Walther G, Carré F. Sports-specific features of athlete's heart and their relation to echocardiographic parameters. *Herz* 2006; 31: 531-543.
- [9] Hornig B, Maier V, Drexler H. Physical training improves endothelial function in patients with chronic heart failure. *Circulation* 1996; 93: 210-214.
- [10] Williams AD, Ahuja KD, Almond JB, Robertson IK, Ball MJ. Progressive resistance training might improve vascular function in older women but not in older men. *J Sci Med Sport* 2013; 16: 76-81.
- [11] van der Wall EE. Long-distance running: running for a long life? *Neth Heart J* 2014; 22: 89.
- [12] Papadakis M, Wilson MG, Ghani S, Kervio G, Carre F, Sharma S. Impact of ethnicity upon cardiovascular adaptation in competitive athletes: relevance to preparticipation screening. *Brit J Sport Med* 2012; 46: 122-128.
- [13] Lawless CE, Olshansky B, Washington RL, Baggish AL, Daniels CJ, Lawrence SM, Sullivan RM, Kovacs RJ, Bove AA. Sports and Exercise Cardiology in the United States: Cardiovascular specialists as members of the athlete health-care team. *J Am Coll Cardiol* 2014; 63: 1461-1472.
- [14] Baman TS, Gupta S, Day SM. Cardiovascular health, part 2: sports participation in athletes with cardiovascular conditions. *Sports Health* 2010; 2: 19-28.
- [15] Zhang KX, Wang Y, Zhang S, Yang YM, Luo ZC, Zeng YJ. Dynamic analysis for blood flow parameters of cardiovascular system on work load. *Conf Proc IEEE Eng Med Biol Soc* 2005; 5: 5551-5554.
- [16] Tanaka H, Bassett DJ, Howley ET, Thompson DL, Ashraf M, Rawson FL. Swimming training lowers the resting blood pressure in individu-

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- als with hypertension. *J Hypertens* 1997; 15: 651-657.
- [17] Bezerra MA, Santos de Lira KD, Coutinho MP, de Mesquita GN, Novaes KA, da Silva RT, de Brito Nascimento AK, Inácio Teixeira MF, Moraes SR. Biomechanical and Structural Parameters of Tendons in Rats Subjected to Swimming Exercise. *Int J Sports Med* 2013; 34: 1070-1073.
- [18] Tanaka H, Bassett DJ, Howley ET, Thompson DL, Ashraf M, Rawson FL. Swimming training lowers the resting blood pressure in individuals with hypertension. *J Hypertens* 1997; 15: 651-657.
- [19] Mehrotra PK, Varma N, Tiwari S, Kumar P. Pulmonary functions in Indian sportsmen playing different sports. *Indian J Physiol Pharmacol* 1998; 42: 412-6.
- [20] Mitchell JH, Haskell W, Snell P and Van Camp SP. Task Force 8: classification of sports. *J Am Coll Cardiol* 2005; 45: 1364-1367.