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The assessment of sports performance by grip pressure using flexible piezoresistive pressure sensors in seven sports events

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Flexible micro-sensors have significant application potential in the field of sports performance evaluation. The aim of this study is to assess sports performance by grip pressure using a MMSS sensor (MXene as the sensitive material and melamine sponge as the substrate, a type of flexible piezoresistive pressure sensor). The grip pressures of expert and amateur players are evaluated in single skills events (golf, billiards, basketball, javelin and shot put) and in skills conversion (badminton and tennis). Indicators (time nodes, intervals, peaks, etc.) related to grip pressure on the handle are collected, analyzed, and identified by artificial intelligence. Finally, the K-Nearest Neighbor (KNN) of artificial intelligence algorithms is employed to identify differences for 400 strokes of tennis players in interval training session. Expert tennis athlete exhibits a higher level of precision, concentration and stability for exert and release of grip force (KNN accuracy of train 95.0%) than amateur (KNN: 84.6%) during single movement, technical conversion, and interval training condition. This research offers a new perspective for evaluating sports performance in hand-held equipment events and presents a feasible direction for facing challenges of flexible wearable technology in practice.

Keywords Assessment of sports performance, Piezoresistive sensors, Kinematic chain, Grip pressure release, Real scenario, Artificial intelligence

The assessment of sports performance has great significance for its scientific, targeting, and precision of training and teaching. It can provide a clear profile and real-time feedback for amateurs, athletes, and coaches to understand training results, identify their shortcomings, and adjust training plans[1–3]. Indexes of biomechanics are used to evaluate sport performance, such as 3D optical analysis tools (Vicon), force plates, and electromyography (EMG)[4,5]. But these evaluation methods are always conducted in laboratory settings and have certain limitations in using test results to guide training in real sport scenarios[6,7]. Athletes and coaches often rely on their observation to assess sport skills or metrics. However, the subjective judgment can be influenced by biases due to limitations of objective data, which will be an obstacle for precise improvements or corrections[8]. In other words, the gold standard evaluation methods can provide precise data in the current field of sports performance evaluation, but they lack authentic background conditions and are complex to operate. Therefore, to address these challenges innovative evaluation methods with precise, convenient, and feasible features in real sports settings is a great strategy for sports performance[9].

The detected changes in force at the micro-interface between body and apparatus is a prevalent challenge, which manifests as the athlete's grip force on the equipment in hand-held apparatus sports. Hand-held apparatus sports involve a direct connection between body and apparatus through the grip force of the hand, thereby influencing the kinematic and dynamic changes of the apparatus directly. However, flexible, miniaturized, and intelligent devices is integral to the precise measurement due to the unique of the grip force interface between the apparatus and hand.

Therefore, the sensors are installed at the interface between hands and the apparatus for relevant force detection to solve the limitations of traditional evaluation methods as aforementioned. In the past, pressure sensors were equipped into handheld instruments to assess the grip strength. However, they are often rigid,

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large-sized and required a reconstruction of athlete's hand grip area on the equipment[10–12]. Moreover, their sensitivity and stability are easily influenced by external factors. Thus, the devices with lightweight, flexible and suitable for assessing sport performance in real scenarios are highly anticipated and well worth constructing. Flexible wearable technology composed various flexible smart sensors (such as flexible piezoresistive pressure sensors (FPPS)) offers some insights in this regard due to their advantages (small size, high sensitivity, wide detection range, ease of portability, etc.). The interfaces between body and device are endowed with highly compatible compatibility by these versatile characteristics[13–15].

The working mechanism of FPPS is the piezoresistive effect. The resistance capability of FPPS changes with the variation of material geometry or morphology of its core components under different external pressures. In essence, the purpose of sensing is realized by recording the relationship between pressure and resistance variations[16]. Consequently, FPPS has been widely applied in body motion detection, health monitoring, and human-machine interfaces, which is attributed to their outstanding features (high sensitivity, wide detection range, rapid feedback, simple structure, low energy consumption, and easy miniaturization)[17,18].

But through the statistics of literatures ($N = 240$), previous studies for FPPS focus on enhancing sensor performance, such as sensitivity, detection range, response time, and durability (Table S1). The main approaches lie in the selection of material, structure, layer, and fabrication technology. For application orientations of FPPS, researches are concentrated on the detection and evaluation of joint extension, wrist radial artery pressure, speech recognition, finger tapping, and plantar pressure (Table S2). However, only a few studies explored complex scenarios such as specific sports techniques, physical fitness, and injury prevention. Given the current research status of FPPS and the limitations of other sensors, FPPS has great potential in sports and health monitor.

In this study, the "grip pressure release" detection device was constructed based on a flexible MXene/melamine sponge sensor (MMSS, a kind of FPPS) as shown in previous study[19]. Firstly, the device was used to measure and evaluate the grip pressure release for expert and amateur players (golf, billiards, basketball, javelin, shot put, badminton, and tennis) in real sports scenarios of once movement. Four indicators related to grip pressure exerted on the handle (T_1: time difference between pressure occurrence and backswing time of lead racket, T_2: time difference between pressure disappearance and end time of follow-through, T_3: pressure duration time, I: pressure peak) were collected, analyzed, and identified by artificial intelligence (AI). Secondly, the grip pressure release of badminton and tennis players was also evaluated for the technical conversion scenarios, as well as the K-Nearest Neighbor (KNN) of AI algorithms was used to investigate the differences among tennis players in interval training conditions. Thirdly, preliminary explanation was given for the neural mechanisms underlying the differences in grip strength release among athletes of different levels. Finaly, the difference between MMSS and existed sport performance evaluation technology was compared. This work not only enriches the existing methods of sports performance assessment via bringing more specific indicators to suit real scenarios, but also promotes the process from research and development to large-scale production for flexible smart sensors.

Methods

Participants

Two athletes (one expert and one amateur, male, aged 18 to 23, height (cm): 177.2 ± 2.9, weight (kg): 67.9 ± 4.1), participated in each of events: tennis, badminton, golf, billiards, basketball, javelin throw, and shot put. The procedures were conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of North University of China (Application No. 202405003), and signed informed consent forms were obtained from all participants including for publication of identifying tested data, information and images in an online open-access publication.

Sensors placement on the hand

The grip pressure release of athletes was tested with varying proficiency levels in seven sports. The functional roles of the hand areas differed in grip tasks[11]. Additionally, the optimal "best contribution zone" of the hand differed for each sports equipment. The "best contribution zone" have been specifically identified for tennis, badminton, and golf in previous studies[4,9,20]. In this study, the sensor placement positions for the seven sports were determined through literature review, expert interviews, and preliminary experiments and were shown in Fig. 1.

Integration of the detection device

The MXene with conductive material and melamine sponge as substrate were prepared for MMSS (NUC, Taiyuan, China). The Ti_3C_2 sponge film was fabricated by a circular melamine sponge (Φ = 7.5 mm) immersed in a Ti_3C_2 colloidal solution. This MXene sponge was placed on a circular interdigital electrode brushed on polyimide (PI) film. Finally, this structure is covered by PI tape, forming a multi-layer structure (PI tape-MXene sponge-interdigital electrode-PI film-PI tape)[9]. MMSS shows high sensitivity of 5.35 kPa^{-1} (1.1–22.2 kPa) and maintain a stable sensitivity of 0.6 kPa^{-1} in an ultrawide high-pressure range (33.3–266 kPa). A recycle 5000 times of load/unload pressure test under 5.5 kPa demonstrate that MMSS have long-term stability and durability[9]. In the actual testing processes, sensors remain its stability suggesting by the I value of the forehand stroke of expert and amateur tennis players has not changed after loading/unloading pressure by hand (> 1000 times) in various testing projects, especially tennis test in previous study[19], meaning that the sensor has great durability under irregular load/unload pressure and extremely high peak pressure conditions. The working mechanism of MMSS is that the pore size of Ti_3C_2 sponge film is changed by varying the loading pressure, thereby altering its resistance capability. The smaller pore size in 3D of the Ti_3C_2-deposited 3D network-structured sponge is caused by the greater the pressure and the lower the resistance value, resulting in the higher current value under a test voltage.

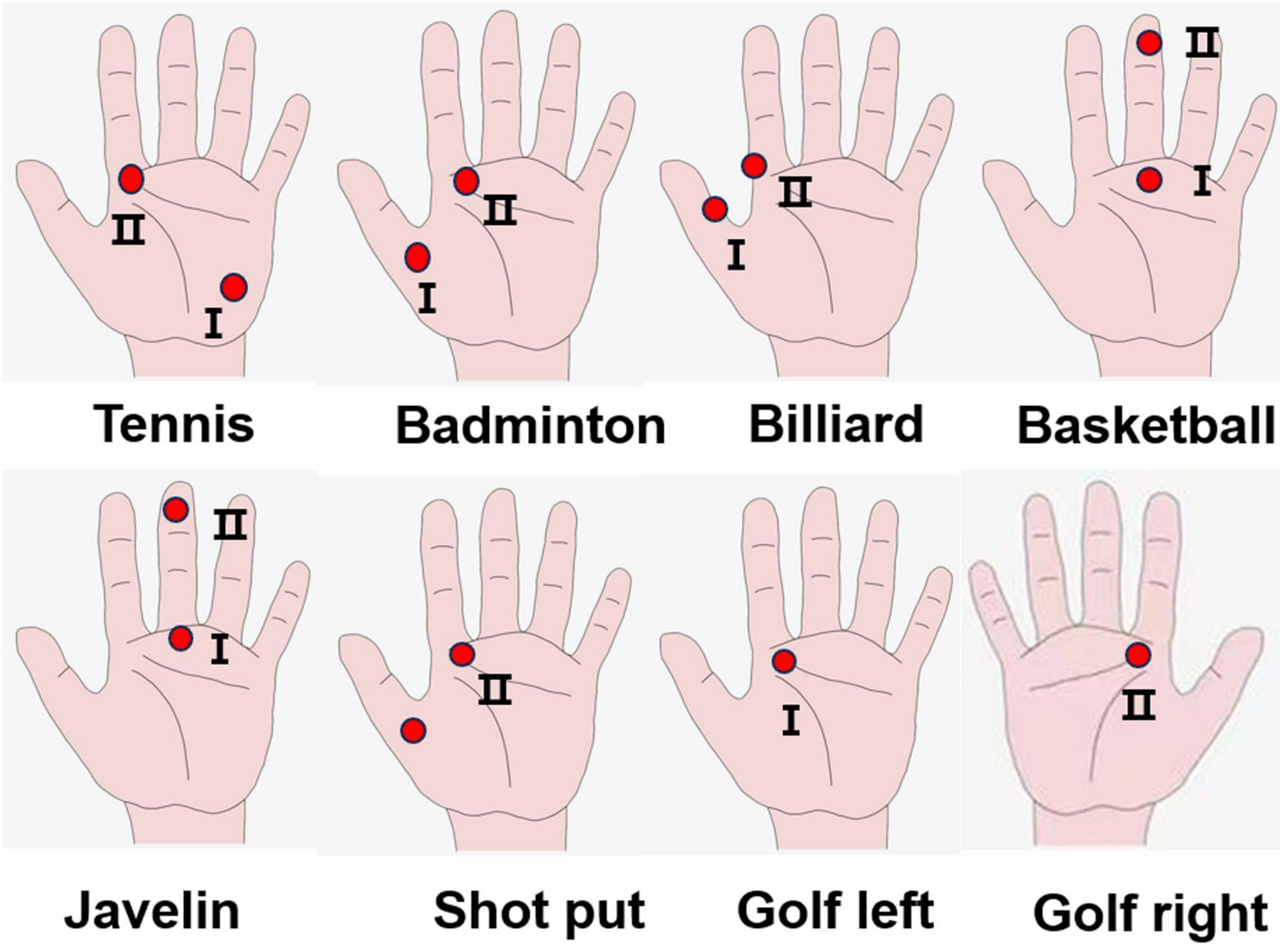

Fig. 1. Optimal contribution areas for grip force release of athletes in seven events.

This device was fabricated at North University of China. As shown in Figs. 2 and S1 in supporting information the display and storage of data were managed using computer software (JDU uppercomputer.exe, Wuxi, China). A laptop and a smartphone were utilized. In addition, a high-speed camera (i-SPEED-5, Ix-Cameras, Britain) was employed to capture the entire movement processes of athletes, facilitating the identification of various motion segmentation points. Timekeeping was facilitated by employing a stopwatch (HS-80W, Casio, Japan). More detailed descriptions about the properties, connection, and fixation methods of the device are shown in the supporting information.

Experimental process

Single skills events: The same equipment and starting position were used for five events: billiards (push stroke), golf (7-iron), basketball (shooting), javelin, and shot put. In each event, each player continuously and intermittently completes their required skill 10 times. (as shown Fig. S2). *Continuous skills events*: *Step 1* involved continuous series of 10 forehand strokes in tennis and forehand overhead smash in badminton, and then athletes returned to the starting point after each strike. *Step 2* entailed four kinds of strokes for tennis players (forehand, backhand, forehand volley, backhand volley) and badminton players (forehand overhead smash, net, forehand overhead smash, net). *Step 3* entailed 400 strokes for each tennis player (per 100 shots for forehand, backhand, serve, and forehand volleys). This involved 20 consecutive flat serves per group with a 30 s break between sets, the serving stance positioned in the deuce court, and 1 m away from the center mark. The other three techniques were performed in sets of 20 strikes each with a 30 s break between sets. The purpose of the 30 s breaks was to induce fatigue in the athletes. Balls were fed using a ball machine (JUGS Sports, Tualatin, OR, USA), with the forehand and backhand techniques starting from the midpoint of the baseline, and the volleys from the semi-court T mark. Throughout the striking process, all balls were valid, and any invalid balls were replaced after each set of testing. All technique tests were completed within a single day.

Key data indexes

Single skills events: As shown in Fig. 3a,b T_1 (s), T_2 (s), T_3 (s) and current peak I (A) were used to assess performance of single skill events. *Continuous skills events*: In the tennis and badminton projects, T_1, T_2, T_3, and I value were also utilized for the single continuous swing technique. Additionally, it was essential to observe changes

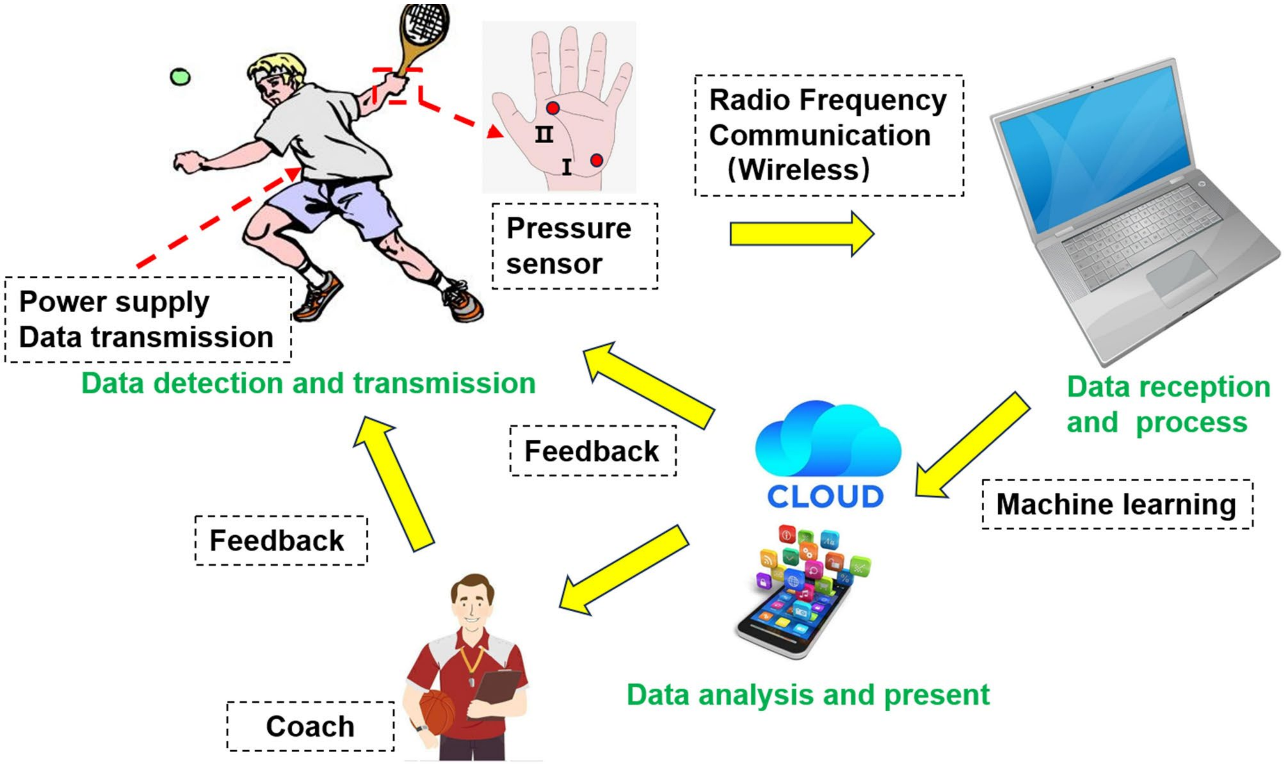

Fig. 2. Schematic diagram of the processes of data collection, transmission, storage, processing, and feedback by an integrated device for athlete grip force release based on MMSS.

in grip strength during continuous and skill transitions. The accuracy of the KNN in intelligent algorithms was compared using 400 samples from expert amateur tennis players.

Data collection and process

The current signals detected from pressure-sensitive MMSS sensor are transmitted to the data storage and transmission device (Fig. S1d) by external wires, and then are collected by signal receptor device (Fig. S1f) installed on the computer based on a wireless technology (radio frequency communication). Origin 2018 was utilized to generate maps during the analysis of native data. In other cases, MATLAB 2021b and Origin 2018 was employed to filter, smooth, fit, and extract features (peaks) from the grip strength waveform. The KNN was used to recognize and classify waveforms for *Step3*. The method of feature extraction and recognition as shown in Part 3 of Supporting information. IBM SPSS Statistics20 was used to complete data statistics, conduct independent sample T-tests, and analyze differences between skills.

Results and discussions

In this study, piezoresistive MMSS sensor is integrated into a device to detect the grip strength release of seven kinds of events for expert and amateur athletes in different scenarios. The main results report that force release in single movement scenarios is more concentrated and precise for expert athletes of billiards, golf, basketball, javelin, and shot put comparing with amateurs. And in continuous striking scenarios force release is also excellent accuracy, regularity, and rhythm accurate for expert tennis and badminton players. Furthermore, expert tennis athlete displays a more energy-efficient and effective for force release in long-time interval scenarios. Using a flexible piezoresistive pressure sensor to evaluate the performance of athletes in different sports events, levels, and scenarios has great originality. This strategy offers a significance perspective for understanding sports performance, and seeks to promote the application scenarios of MMSS and other functional wearable sensors for focusing on popularization and exploration.

The tested, transmitted, and analyzed data (T_1, T_2, T_3, and I value) of single (billiards (push stroke), golf (7-iron), basketball (shooting), javelin and shot put) and continuous skills events (tennis (forehand strokes) and badminton (forehand overhead smash)) are shown in Table 1; Figs. 3 and 4a–d. Table 1 indicates significant differences ($P < 0.01$) in the push stroke skill of billiard regarding indicators T_1, T_2, and T_3 between expert and amateur players. However, there is no significant differences ($P > 0.05$) in the I value. Hands of expert billiard player are in relaxation state after receiving the start signal and grip strength is only applied when here need to strike the ball with a more focused exertion of force in backswing-stroke stage (Fig. 3a). After stroking, expert billiard player quickly recovers to relaxed state in follow through stage. In contrast, for amateur billiard player grip strength is applied to the cue immediately after seeing the signal (aiming stage), which last longer than that of the former (Fig. 3b). And they do not relax after stroke in follow through stage. These results indicate that

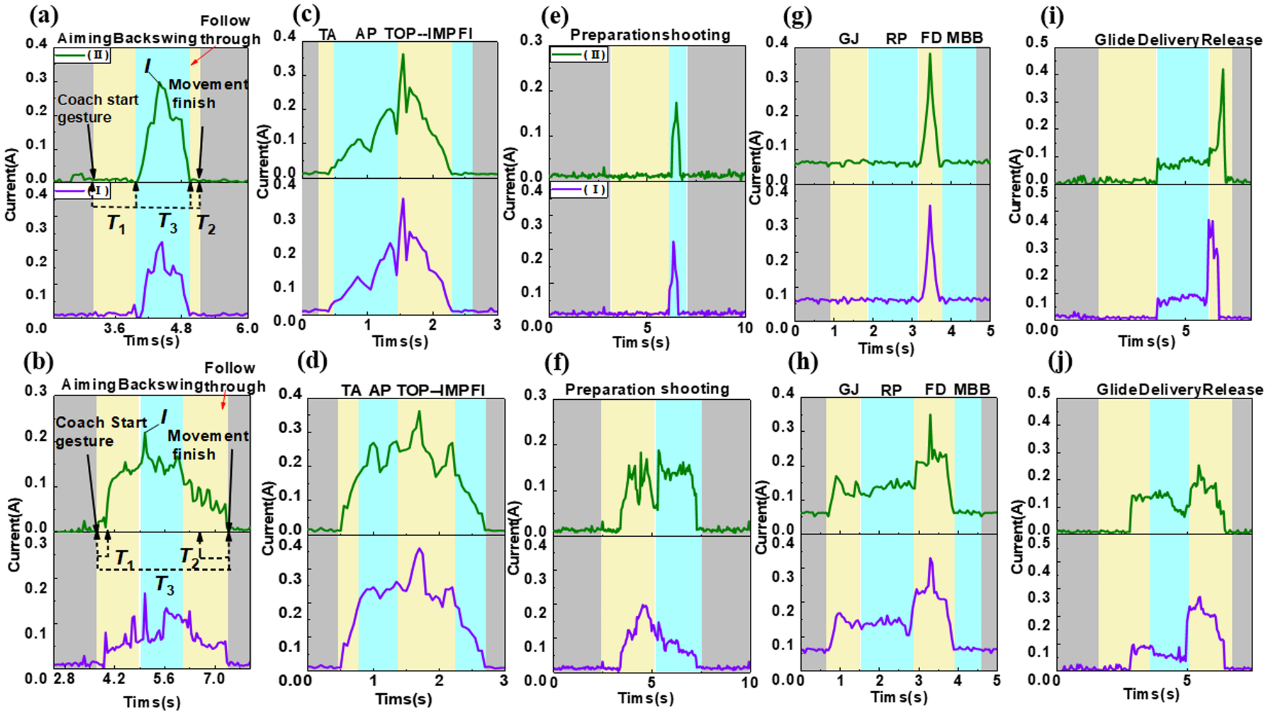

Fig. 3. Current curves detected by MMSS sensors I (violet line) and II (olive line) of grip pressure in billiard, golf basketball, javelin, and shot-put: the push stroke of expert (**a**) and amateur (**b**) billiards players; the 7-iron of expert (**c**) and amateur (**d**) golf player (*takeaway (TA), left arm parallel (AP), top of swing (TOP), impact (IMP), and finish (FI).); the shooting of expert (**e**) and (**f**) amateur basketball players; the throw of expert (**g**) and amateur (**h**) javelin players (*gripping the javelin (GJ), carrying the javelin during the run-up (RP), final delivery (FD), and maintaining body balance (MBB)); the throw of expert (**i**) and amateur (**j**) shot-put players.

expert billiards player have superior rhythm and timing in the grip strength release compared with amateurs, rather than the difference in force extremum. Similarly, there are significant differences ($P<0.01$) between expert and amateur golf players in terms of indicators T_1, T_2, and T_3, and no significant difference ($P>0.05$) between the two levels in I value (Table 1). The reasons for the differences in T_1, T_2, and T_3 are the seem as the case of billiard players. And a relaxed hand state is found from expert golf player during the TA phase before the swing and the FI phase after the swing, whereas grip force is applied by the corresponding amateur player during both of stages (Fig. 3c,d).

The same phenomenon is also found in basketball project. The grip force is applied more concentrated by expert basketball player during the shooting phase (Fig. 3e), and significant grip strength signals are found during the preparation phase for amateur players (Fig. 3f). However, the javelin event has different results. The peak current I shows a significant difference ($P<0.01$), demonstrating that expert javelin athlete generates the greater force during the Forward Drive (FD) phase (Fig. 3g) and amateur player exhibits significant grip strength during the GJ-RP-FD stage (Fig. 3h). As shown Figs. 3i, j; Table 1, the grip pressure release of expert and amateur shot-put players is relatively similar. T_1 and T_2 are without significant differences ($P>0.05$) showing that shot put have different results compared with billiards, golf, basketball, and javelin. Through on-site communication with coaches and athletes, it is discovered that the weight of the shot itself cover the process of the athlete's grip strength release. The I value have the significant difference ($P<0.01$) which indicates that the greater force is applied by expert shot-put athlete to the shot during the release phase.

Although there are differences among five scenarios in single movement events, grip force is applied more concentrated and precise by expert players of billiards, golf, basketball, javelin, and shot-put within single movement setting. And grip strength is also is controlled more precisely and centrally by expert players than the amateur at the critical moments of impact or release in single movements of these five events. Previous findings are also partly corroborated in this study. For instance, there is no significant difference in the peak force values (I) at specific positions between expert and amateur for golf during the "impact" phase[12]. Previous research reported no significant difference in the force exerted during the stroke between expert and amateur billiards athletes[21,22]. In addition, these findings demonstrate that athletes reach peak force in the phase of releasing for shot put and javelin throwing, which align with previous studies[23,24]. And grip force is shown more consistent for expert golfer than amateur at specific stages, which is consistent with previous research. Importantly, for basketball shooting motion the grip force changes described by coaches and athletes in previous are tracked and displayed by these results based on MMSS sensor.

Previous researches focus on the correspondence relationship between equipment and body at specific grip force points. This study not only examines correlation this relationship but also is concerned with the overall

	Event	Indexes	Expert (Mean ± SD)	Amateur (Mean ± SD)	95% confidence interval (lower, upper)	T value	P
Billiards	T_1 (s)	0.36 ± 0.06	0.04 ± 0.01	0.32	0.02	15.42	0.00*
	T_2 (s)	− 0.23 ± 0.04	0.07 ± 0.07	− 0.30	0.02	− 12.31	0.00*
	T_3 (s)	0.34 ± 0.03	0.64 ± 0.16	− 0.29	0.05	− 5.71	0.00*
	I (A)	0.26 ± 0.03	0.25 ± 0.02	0.00	0.01	0.40	0.69
Golf	T_1 (s)	0.47 ± 0.07	0.05 ± 0.08	0.42	0.03	12.41	0.00*
	T_2 (s)	− 0.15 ± 0.04	− 0.06 ± 0.03	− 0.09	0.01	− 5.72	0.00*
	T_3 (s)	0.33 ± 0.02	0.95 ± 0.05	− 0.62	0.01	− 34.74	0.00*
	I (A)	0.34 ± 0.03	0.35 ± 0.04	− 0.01	0.01	− 0.79	0.43
Basketball	T_1 (s)	2.48 ± 0.27	0.31 ± 0.15	2.17	0.09	21.84	0.00*
	T_2 (s)	0.11 ± 0.01	0.51 ± 0.05	− 0.39	0.02	− 23.76	0.00*
	T_3 (s)	0.88 ± 0.09	4.35 ± 0.28	− 3.47	0.09	− 37.06	0.00*
	I (A)	0.14 ± 0.03	0.18 ± 0.03	− 0.04	0.01	− 2.62	0.02
Javelin	T_1 (s)	1.34 ± 0.17	0.47 ± 0.39	0.86	0.13	6.35	0.00*
	T_2 (s)	− 0.15 ± 0.15	0.24 ± 0.04	− 0.39	0.04	− 7.82	0.00*
	T_3 (s)	0.94 ± 0.47	5.07 ± 0.67	− 4.13	0.26	− 15.80	0.00*
	I (A)	0.41 ± 0.02	0.23 ± 0.01	0.17	0.01	19.50	0.00*
Shot put	T_1 (s)	0.06 ± 0.07	0.08 ± 0.07	− 0.03	0.03	− 0.66	0.55
	T_2 (s)	0.11 ± 0.02	0.10 ± 0.02	0.00	0.01	0.61	0.55
	T_3 (s)	2.16 ± 0.14	3.72 ± 0.68	− 1.55	0.22	− 7.00	0.00*
	I (A)	0.41 ± 0.02	0.28 ± 0.07	0.13	0.02	5.30	0.00*
Tennis	T_1 (s)	0.39 ± 0.05	0.16 ± 0.05	0.18	0.28	9.83	0.00*
	T_2 (s)	− 0.22 ± 0.02	− 0.11 ± 0.04	− 0.14	− 0.07	− 6.97	0.00*
	T_3 (s)	0.50 ± 0.03	0.77 ± 0.12	− 0.35	− 0.18	− 6.77	0.00*
	I (A)	0.33 ± 0.01	0.34 ± 0.04	− 0.03	− 0.01	− 0.80	0.43
Badminton	T_1 (s)	0.38 ± 0.06	0.17 ± 0.04	0.16	0.27	8.25	0.00*
	T_2 (s)	− 0.26 ± 0.05	− 0.12 ± 0.02	− 0.18	− 0.10	− 7.32	0.00*
	T_3 (s)	0.50 ± 0.03	0.83 ± 0.06	− 0.38	0.29	− 15.97	0.00*
	I (A)	0.34 ± 0.03	0.32 ± 0.02	0.00	0.03	1.81	0.87*

Table 1. Analysis of grip pressure waveform indexes for expert and amateur groups of single (billiards, golf, basketball, javelin and shot put) and continuous skills events (tennis and badminton). *$P < 0.05$ indicates the significant difference.

grip force conditions during certain stages of a single movement. For example, expert billiard athlete has a concentrated grip during the push stroke, while amateur exert force for longer time and has the characteristic of uneven changes in grip strength (Fig. 3a,b; Table 1). It can be inferred that strategic decision is slowly done and grip force is applied less accurately and concentratedly by amateur golf player. These results also demonstrate that the ball is held by expert basketball athlete with a relaxed posture from the holding preparation to the final grip release. The force is quickly exerted from the palm root to the fingertips to flick the ball (as indicated by sensors I to II), and finally release grip pressure when decide to carry out shoot (Fig. 3e,f). In contrast, grip force amateur is applied on the basketball from preparation posture to final release. The visible transfer process is not found for amateur basketball player from the palm root to the fingertips and their exertion time is longer than expert athlete for grip pressure.

Combining key points with process evaluation can provide coaches and athletes more comprehensive feedback in evaluating performance using grip force (Fig. 3d), since movement is a continuous process, not just a series of key points[25,26]. In summary, the timing and sequencing of the force applied to an implement (i.e., racket) or object (i.e., ball) by the hand in sport is arguably of greater importance than the magnitude of applied force alone.

In Fig. 4a–d; Table 1, there are significant differences ($P < 0.01$) for the forehand in tennis and the forehand overhead smash in badminton between expert and amateur athletes for the T_1, T_2, T_3 indicators, but no significant differences ($P > 0.05$) for the I value. This parallels the outcomes of the billiard and basketball events, demonstrating the precise control capacity of expert athletes. As shown in Fig. 4, the grip force application is more concentrated during continuous hitting for two events. Expert tennis and badminton athletes have more time to relax between each hitting. This result indicates that expert tennis and badminton athletes have a clearer rhythm in the grip force release and more mature application of various techniques.

For badminton, there are two main types of sport skills: power and control[27]. For example, the aim of smash is “speed” which originates from the athlete’s explosive power[28]. The net, on the other hand, relies on the athlete delicately control grip force to produce the desired effect. The patterns of hand relaxation and tension are also key factors for tennis, meaning efficient transfer of force from hand to racket during the stroke[9]. Expert badminton athlete is more relaxed between forehand overhead smash and net, exhibiting the better explosive

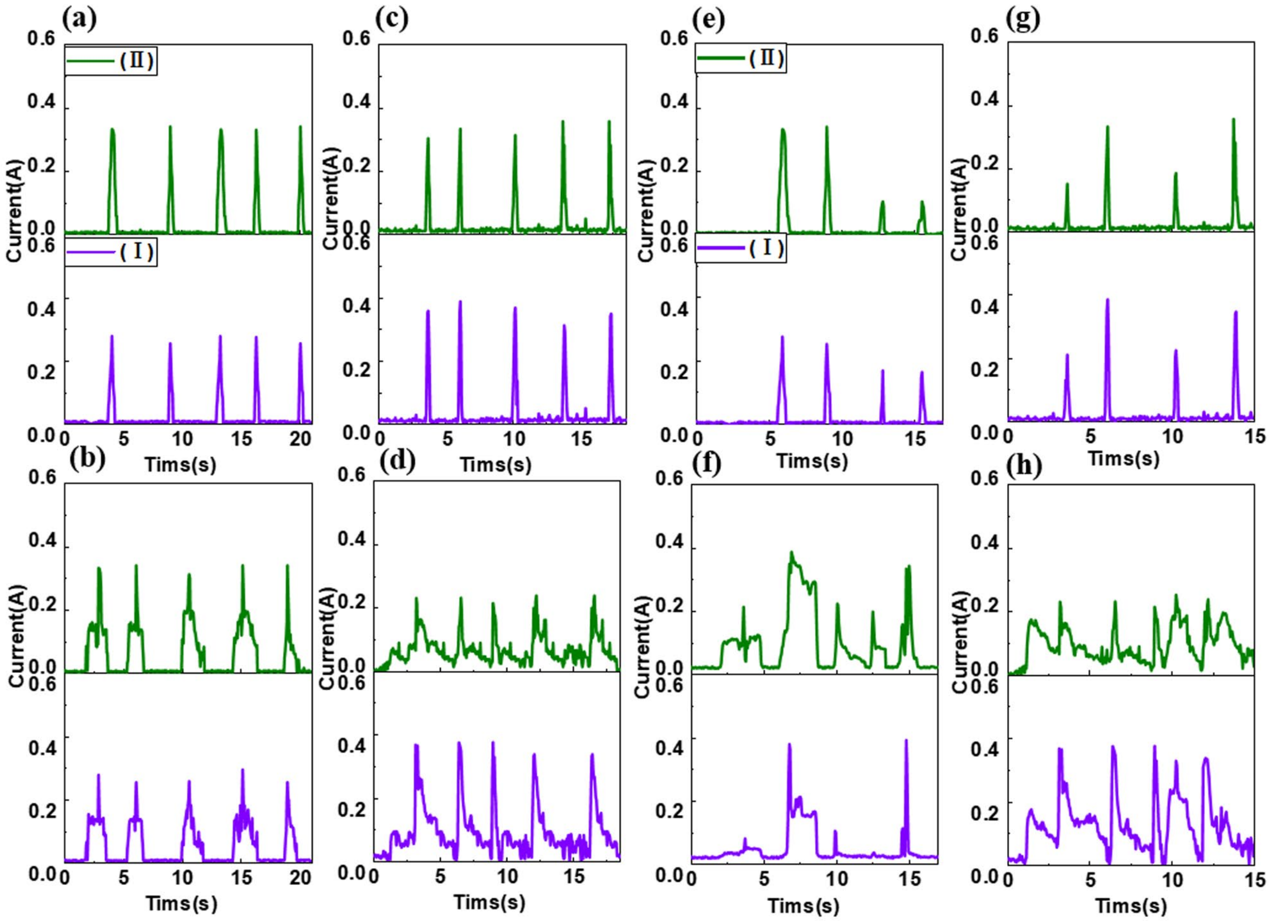

Fig. 4. Current curves detected by Sensors I (violet line) and II (olive line) of grip pressure in continuous strokes for tennis and badminton: continuous forehand strokes of tennis expert (**a**) and amateur (**b**) players, continuous forehand overhead smash of badminton expert (**c**) and amateur (**d**) players, skills conversion (**e**) tennis expert player and (**f**) tennis amateur player, skills conversion of (**g**) badminton expert player and (**h**) badminton amateur player.

power during forehand overhead smash and grip control during net (Fig. 4g). The ability to have shorter current waveforms and to remain relaxed between hitting is found for expert tennis athlete (Fig. 4e), suggesting that their contraction and relaxation of muscles are accurate and regular during the techniques transition between difference skills. However, grip force of amateur is not concentrated during the transition from difference skills (Fig. 4f,h). They lack relaxation phases in the continue and conversion condition. But the timing and rhythm of their grip force application can be regulated by amateur tennis player based on the “signature” of the grip force of expert tennis athlete in the hitting. Hence, the ability of the integrated device based on MMSS to identify and present the “control force” phenomenon is highlighted by these results.

Compared to previous studies, the information of “grip force” is expanded by this study for tennis and badminton players during drives. The grip force characteristics as well as its relationship with racket head speed and forearm vibration, primarily focusing on the peak grip force at specific moments have been investigated by many studies in tennis players[29,30]. Additionally, researchers suggest that the peak value occurs before the point of impact for high-level athletes[31,32]. And they argue that the peak value remains consistent for both professional and amateur tennis athlete during stroke[33]. However, the overall grip force curve referred to as a “signature” is not analyzed in previous studies, which includes the continuous curve features, particularly the quiet intervals between consecutive strokes. Similarly, the use of “signatures” to provide feedback in training, such as guiding athletes to release grip force and applying it consistently to enhance performance, has not been explored. Correspondingly, this study assesses the grip force value at specific moments during individual strokes to evaluate the entire grip force curve, and focuses on continuous strokes involving various skills.

Simultaneously, KNN is employed to identify differences among large samples of tennis players under interval training conditions, offering feedback to player on how to release grip force consistent, accurate, and efficient. Base on the accuracy of the KNN algorithm for identifying 400 strokes. 30% of the samples as the test set and 70% of the samples as the train set are randomly selected by KNN intelligence algorithm. *The* accuracy of test set is 92.5% and train set is 95.0% for expert tennis player (Fig. 5a,b), which are better than amateur player with 74.2% and 84.6% (Fig. 6a,b).

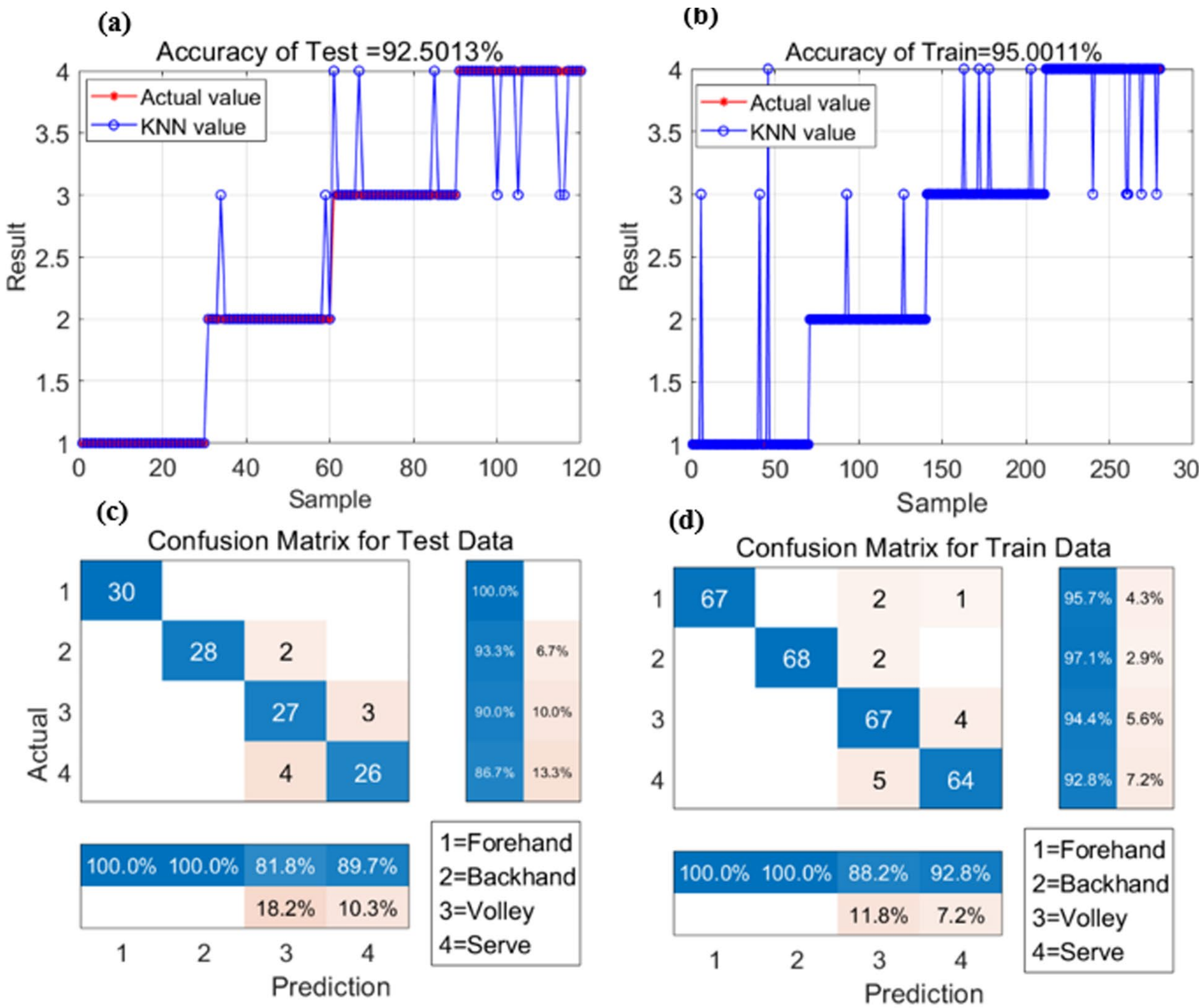

Fig. 5. The KNN algorithm was used for intelligence recognition of data: comparison of test data prediction results for expert tennis player (**a**), comparison of train data prediction results (**b**), confusion map of test data (**c**), and confusion map of train data (**d**).

The main confusion in techniques occurs between volley and serve for expert player (Fig. 5c,d). A small portion of the hitting can be easily confused due to the similarity between the grips for volley and serve. However, the varying degrees of confusion is found in the seam time of all four skills for amateurs in the confusion matrix (Fig. 6c,d). This indicates that expert tennis player always performs their techniques more stably over a certain period. The grip force is applied more centrally, suggesting by the accuracy of consecutive 400 strokes from expert tennis player. These cases suggest that amateur tennis player exhibit poor stability in longtime interval condition. This work provides a method to help players self-assess their sports performance in real scenarios without the presence of a coach. In summary, the grip force of expert tennis athlete is applied more centrally, showing a clearer and more stable rhythm of relaxation and grip force application in continuous stroke and interval training settings.

The movement process of athletes is driven by the muscles, bones, and joints, and directly regulated by the nervous system[34]. On this basis, the influence of psychology should not be overlooked, which is mainly concentrated on the perception of movement[35]. Elite athletes have achieved automatic stage in their motor skills with their motor neurons occurring precisely, regularly, and in a sequenced in the cerebral cortex, to form complex, chained, and proprioceptive motor conditioned reflexes[36]. This enable professional athletes with a more defined "kinematic chain" during the movement process, where muscle contraction and relaxation are precise and rhythmic[37].

For example, there is an obvious difference between expert and amateur javelin players in terms of grip strength during the holding, runway, final throw, and balance maintenance phases. For expert javelin player the grip strength is only used during the final throw phase, which lasts approximately 0.4 s. They are relaxed before the final throw phase (Fig. 3g). In this study golf expert athlete is relaxed in the TA-AP phase, while grip strength starts to appear from AP-TOP. The instant force is generated from TOP-IMP, and the grip strength disappears

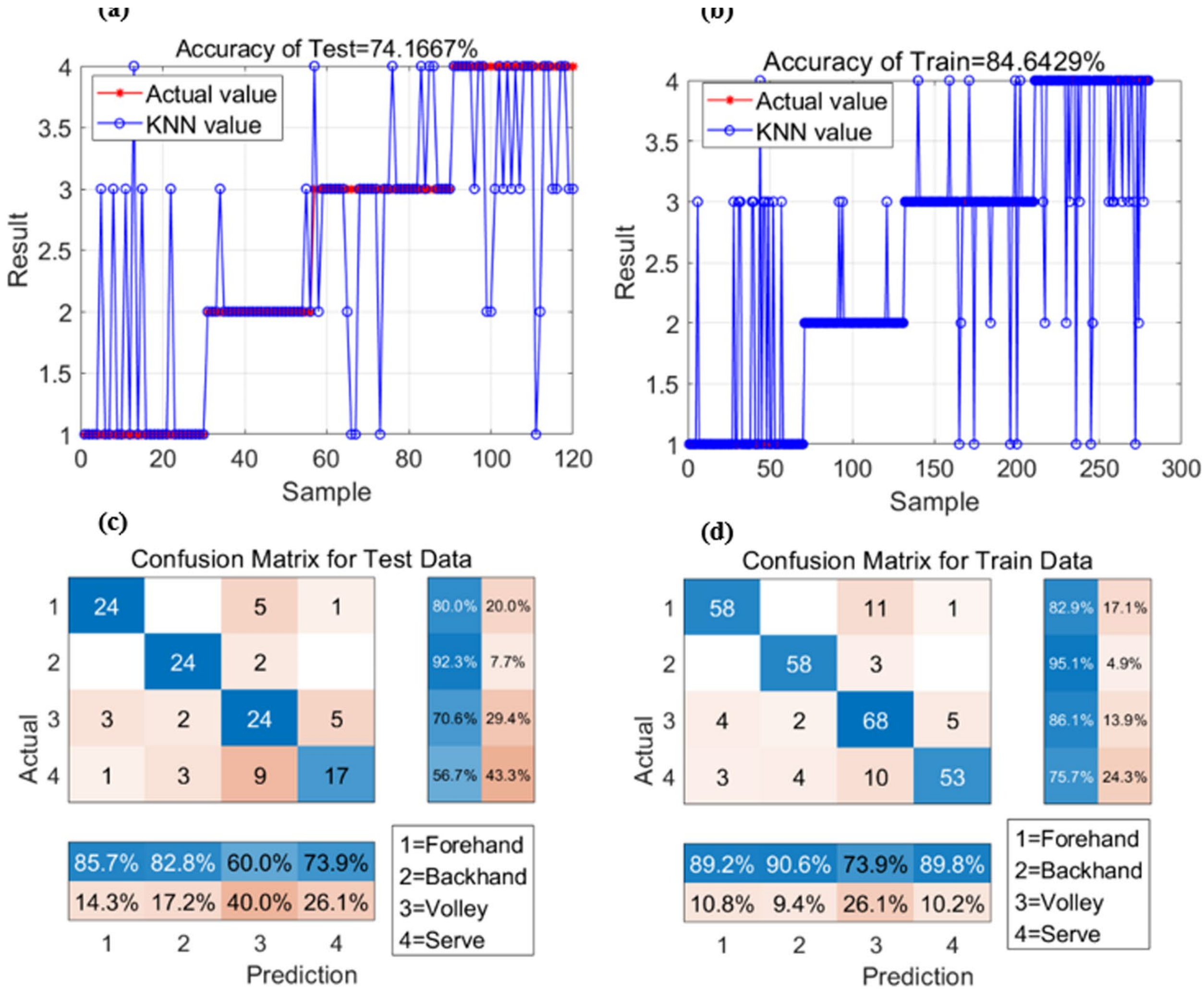

Fig. 6. The KNN algorithm was used for intelligence recognition of data: comparison of test data prediction results for amateur tennis player (**a**), comparison of train data prediction results (**b**), confusion map of test data (**c**), and confusion map of train data (**d**).

from TOP-FI (Fig. 3c,d). Amateur golf athletes' motor skills are in the stage of generalization or differentiation, and their motor neurons for controlling specific movement programs have not formed a fixed sequence and rhythm in the cerebral cortex.

Therefore, muscles are controlled by amateur through activation and relaxation, which are irregular during movement. For example, for amateur javelin player a tight grip is kept on the apparatus after holding it and form runway to final throw. The final throw phase lasts longer, and the explosive force is not exerted (Fig. 3h), as well as the same pattern in any of the phases is not found for amateur shot up player (Fig. 3j). These differences become more pronounced for tennis and badminton in continuous striking and skills conversion scenarios. For instance, in these scenarios expert athletes can relax between each movement with precise hand perception and without applying grip force on the apparatus (Fig. 4a,c,e,g).

In contrast, due to the deficient motor perception control of hand movements in the cerebral cortex, amateur players of billiards, golf, basketball, javelin, and shot put often fail to relax their hand quickly between each strike or during technical transitions, resulting in "noise" in pressure waveforms (Fig. 4b,d,f,h). Furthermore, expert athletes of billiards, golf, basketball, and javelin already have a mature "dynamic chain", which allows them to save energy during long time training[38]. And the action of each strike is determined by efficient motor perception, which helps improve the muscle efficiency. This effective process enables them to maintain stability in their movements during long time interval training[39]. For example, train set (70% sample size) is 95.0% using the KNN analysis for the accuracy of the expert tennis athlete's 400 strikes, which is higher than the 84.6% accuracy of amateur (Figs. 5b and 6b).

The primary kinematic methods for sports performance assessment include 3D motion capture technology[40], EMG[41], force platforms[42] and inertial measurement units (IMUs)[23,24]. These mature technologies provide comprehensive kinematic and dynamic data, enabling athletes and coaches to better understand and improve sports skills. However, they also have disadvantages such as a lack of real scenarios, high costs, complicated usage, and the data obtained by them is highly specialized and difficult to understand. Additionally, they focus on presenting the state of athlete and the apparatus when depicting data, such as acceleration, angular velocity, linear velocity, applied force and reaction force, muscle activation, and force transmission.

However, the direct relationship between the apparatus and the human body in terms of "force" for sports of handheld apparatuses are not effectively captured by these methods. In these skills, grip strength contributes to the overall force chain minimally, yet its primary function is "release"[8,41]. Therefore, a more suitable method is expected to monitor and assess grip strength across the hand-to-tool interface. It can complement the existing assessment methods and make the results more comprehensive and easier. Based on the above research results, the advantage of the MMSS over existing pressure sensors lies in its miniature size and weight, ease of use without damages the apparatus. This wearable flexible sensor also does not interfere with the athlete's performance like hardness pressure sensors.

Conclusion

This study evaluates the sports performance of expert and amateur players in single-movement scenarios (billiards, golf, basketball, javelin and shot put) and skills conversion scenarios (tennis and badminton) based on the MMSS within the Min-interface between hand and equipment. In addition, the KNN algorithm is applied to study the long time hitting of tennis players in interval training scenarios. Expert players exhibit more precise and efficient for grip force utilization along with better rhythmicity. The stability and accuracy of the MMSS sensors are also verified and reflects by these results. The evaluation device based on MMSS is convenient for application and simple with understanding, showing that it is suitable for real sports scenarios. This work offers a new perspective for sports performance assessment and provides a reference for the application of flexible intelligent wearables. However, this study lacks a concurrent testing process with other methods such as IMUs hinders (a more comprehensive description of athletic performance), and fails to demonstrate the correlation between grip force release and other segments within the kinematic chain.

Data availability

The datasets used and analysed during the current study available from the authors (wangliu@cupes.edu.cn, kehuzhang@qq.com) on reasonable request.

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The authors declare no competing interests.

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