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Design enhancement of overall Paralympics wheelchair for para table tennis competition

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Abstract

This study focused on enhancing the performance of the para table tennis player by implementing design modifications to the wheelchair to increase the sweep area of the player. In this paper, a detailed study of the pressure distribution on the player's seat during play was performed to facilitate potential enhancements to the wheelchair that would alleviate issues that could arise from long hours of training and actual competition. Some of these issues include the discomfort and fatigue that could develop from an imbalanced posture resulting in imbalanced seat pressure distribution exerted on the Gluteus Maximus, as well as pressure sores that could develop during training and competition. Such issues impact the immediate and long-term development of competitiveness in the player. Through a systematic and quantitative understanding of the situation, further structural enhancements to the wheelchair, as well as modifications to the training methodologies, strategies and techniques of game play could be implemented.

Keywords

Pressure mat, pressure distribution, pressure sores, para table tennis, optimized reach, sweep area, wheelchair

Introduction

Para table tennis allows athletes with varying ability to participate and compete in the sport. Athletes with limited upper body mobility are also able to participate using their personal mobility device, like a wheelchair. As the sport develops from participation to excellence, the goal is no longer about just competing, but rather winning. Para table tennis athletes in Singapore have reached this juncture, compelled to compete against the best athletes. Apart from the athlete's ability, the role of equipment has a strong influence on how effectively they can move. Most of these athletes do not have a personalized personal mobility device optimized to their physical ability to play the game. Rather, the common strategy adopted is to make do with existing generic equipment to compete in the sport. A review of studies in sports science on Para-Sports has revealed a strong emphasis on terrestrial and aquatic movement strategy for Para-Athletes^{1, 2}, strategic demands of Para-Team sports³, or generic strength training requirements for Para-Athletes⁴. Studies attempting to investigate a specific class of athlete in Para-Sports are still limited, especially for Para-Table tennis athletes⁵.

In a previous study, several aspects were explored to determine how para table tennis play can be improved. This included reworking the seat cushion for player comfort and improving the sensitivity of personal mobility devices. Further field observations and discussion with the users revealed their latent need to expand playing reach. The player's physical range of movement impacts their biomechanical reach limitation, which in turn affects the table coverage during a game. Thus, the development process shifted from refinement of equipment mechanism to strategizing the player's biomechanical pivot point for extended reach. The coaching staff specified two players requiring the equipment intervention for strategic interest in a major tournament.

Wheelchair modifications and enhancements

Class 1 Athlete

The main limitation faced by the Class 1 athlete was the unnatural position due to anchoring of his arm on the wheelchair push handle, which aids him in extending his reach forward. Due to the lack of triceps and control of muscles beneath the chest level, the athlete must anchor his arm onto the handlebar at the top of the wheelchair backrest as shown in Fig. 1(left).

However, such position is deemed to be un-ergonomic due to the unnatural posture such as the bending of shoulders. As shown in Fig. 1, the comfortable position of a resting arm should be in line with an upright sitting position. To realize this position, the handle grip has to be brought forward by a small distance in order for the athlete to feel comfortable and yet not lose his balance during the course of playing. The difficulty of the current push handle caused the player's elbow to be forced closely towards his torso, thus restricting his movement and functional reach. The aim was to modify the form and dimensions of the handle grip such that it would allow the player to shift into the optimal positions. The handle grip was shifted further sideways, away from the

athlete's torso by 0.07 m (Fig. 1, right). In addition, the handle grip was shifted forward 0.04 m.

Figure 1. (Left) Placement of idled arm on the push handle of wheelchair in order to extend the athlete's reach of the other arm; (Right) Ideal arm position with an upright torso posture. This is a frontal view of athlete, sitting in the wheel chair and with his left arm around the proposed handle grip.

Systematic concept generation and concept proofing were conducted together with the athlete. Biomechanical simulations using finite element and force analysis were performed using PTC Creo Simulator (Fig. 2), with an assumed maximum load of 78.48 N. This value was obtained via a measurement of the maximum force exerted by the athlete on a spring force gauge in the forward direction. Stainless steel was chosen as the material of the improved version of handle grip and its properties required for simulation are summarized in Table 1. Prototypes were fabricated based on this design.

It was expected that the cross-section at point B would experience the greatest shear stresses since it was located furthest from the possible torque loads exerted by the athlete during game play. From Fig. 3, the calculated stresses for Point u were the maximum anticipated stress of $\sigma_{\max} = 64.893$ MPa and minimum anticipated stress of $\sigma_{\min} = -3.939$ MPa. For point v, the calculated stresses were $\sigma_{\max} = 32.789$ MPa and $\sigma_{\min} = -7.808$ MPa. By entering the largest of these values (64.893) for maximum loading stress in Eq. (2) with a safety factor of 2.5, the maximum material yield stress allowed was 162.23 MPa.

$$\text{Factor of Safety} = \frac{\text{Material Yield Strength}}{\text{Maximum Loading Stress}} \quad \text{Eq.}$$

$$(1) 2.5 = \frac{\text{Material Yield Strength}}{64.893 \text{ max}}$$

$$\text{Material Yield Strength} = 162.23 \text{ MPa}$$

Since the given material tensile yield strength of the selected stainless steel AISI Type 304 is 215 MPa (Table 1) was much larger than 162.23 MPa, the selected material was well suited for the fabrication of the handle. Cushioning sleeves selected had an internal

diameter of 8 mm. Due to their elastic property, the sleeves were able to be formed with a close fit over the 10 mm diameter handlebar. The sleeves allow for comfort of the athlete and reduce abrasion to the arms as he leverages on the handle during game play.

Figure 2. (Left) Overall design of the handle grip for Class 1 athlete with various mechanical constraints set in place; (Right) Simulation analysis on mechanical stress experienced by the handle grip

Figure 3. Cross sections of two points, A and B, along the axis of handle.

Table 1. Material Properties

Material Description	Stainless Steel AISI Type 304
Tensile Strength, Ultimate	505 MPa
Tensile Strength, Yield	215 MPa
Young's Modulus of Elasticity	193,000 – 200,000 MPa
Shear Modulus	86,000 MPa
Poisson's Ratio	0.29
Density	8000 kg/m ³

Class 2 Athlete

The Class 2 athlete had a much more challenging problem than the Class 1 athlete. This athlete had to operate in a motorized wheelchair and leaning too far out would cause him to lose his balance due to the absence of support. A cord is typically added that allows freedom of movement with elasticity to enable the athlete to return to an equilibrium position easily after reaching out for an attack. The current addition to the wheelchair is a one-piece elastic band which holds the athlete's upper body upright (Fig. 4). The strap is tied to the wheelchair and the upper body to support the athlete when leaning to the left and right. Although the thick elastic strap gave a sense of security and support, the insufficient strap length causes limitations of reaching forward and to extreme corners, thereby hindering performance.

Figure 4. Thick elastic band attached to the back rest

In the new solution shown in Figs. (5) and (7), a bungee cord was attached to a Velcro belt, 0.06 m thick, by looping it through a 0015m hole that was punched through the belt before securing it with two aluminum eyelets. The eyelets were attached with a tarpaulin eyelet puncher (Fig. 6). This was done to protect the edges of the belt fabric from wear and tear due to sliding friction during usage. The velcro belt was secured over the athlete's upper torso, while the bungee cord provided the elastic response that enabled the athlete to use less effort in returning to an equilibrium position after an overreaching action (Fig. 5).

Figure 5. (Left) Securing of Class 2 athlete's torso when performing overreaching motions; (Right) Strap based constraint for the athletes

Figure 6. Fabrication of Harness

Figure 7. Completed Harness

The second part of the current study aimed to achieve greater enhancement in the long-term competitiveness of the players during training and game play by investigating further the effect of their postures and seat arrangement on their respective wheelchairs. Measurements were carried out with the pressure mat sensors attached to the seat cushions and the relations between seat pressure distributions and postures of the player were obtained. This information was used to ensure that the player was able to achieve comfort and avoid development of pressure ulcers over prolonged periods of action, through the enhancement of play techniques and strategic position of the player on his seat, so that the effectiveness of his maneuvers could be maintained. Pressure ulcers, also commonly known as pressure sores, bedsores or decubitus ulcers, can develop very quickly sometimes within hours⁷. The development of pressure ulcers is mainly caused by an uneven match between the skin and subcutaneous tissue to withstand the external load. The reported values for pressure ulcers in the U.S. healthcare facilities are as high as 15.5%, with 28.0% located at the scrum and 17.2% at the buttocks⁸. Academic studies for pressure ulcers have also been carried out in the European academic hospitals and have reported occurrence figures of 18.1%. Pressure ulcers will deteriorate over time, causing serious harm or even death, hence posing a great risk to the athletes who are likely to exert greater than normal stresses to their lower body during competitive play.

Methods

Sweep area test

To analyze the sweep area (SA), simple pen and paper drawing was combined with multi angle video capturing to identify the athletes' reach on the table tennis table. Shoulder flexion of the athletes was the main focus of this test. Through the flexion movement, the sweep area could be plotted out. This area was very similar to the shape of a compass,

where the athletes' shoulder joint served like a pivot and his arm gave a full semicircle while sweeping the table.

Positioned at a fix position within 30 cm from the edge of the table to the athletes' trunk, the measurement was taken. For safety consideration, as well as getting a more accurate result, the wheelchair was locked to secure his seat position. As shown in Fig. 8, arc A represented his comfort reach with no difficulty, while arc B would be his maximum reach in which he extended his arms all the way out.

To replicate a competition environment, the athlete would perform this test while locking his elbow to keep his master arm straight. Keeping his non-master arm anchored and secured to the push handle of the wheelchair, he had to perform several sweeps to simulate his common behaviours during an actual match.

Figure 8. Sweep Area Test – Arc A represents the athlete's normal reach while Arc B represents his maximum reach

One player each was chosen from Class 1 and Class 2 pools of players to perform this test. An effective SA of approximately 28.8% and 29.7% were recorded for Class 1 and Class 2 players, respectively. Moreover, the recorded sweeping times (mean value from five readings) were 4.0 sec and 3.7 sec for Class 1 and Class 2 players, respectively. These values served as a benchmark for this study of the mechanical improvement of the wheelchairs.

Seat Pressure Distribution

Seat pressure distribution was measured using the Pressure Sensor Tex pressure mat during the maximum reach test, reach timing test, and static posture test.

Pressure Sensor Tex

Further maximizing the athletes' playing capabilities would involve a certain adjustment of their playing style, such as the seated position in which they placed themselves. Due to the inability to control their Gluteus Maximus muscle, they would be unable to feel the excess pressure being exerted on themselves, especially from their prolonged sitting during the course of a match, which typically lasts for 30 minutes. In the long run, this accumulated pressure would affect their performances during competitive play as well in their daily lives, due to the existence of pressure sores accumulating at the pressure hot spots.

To remedy these issues, one of the conceptual solutions would be identifying the area and magnitude of the pressure point, and taking measures to reduce that pressure by adjusting the seated position. The methodology to retrieve these pressure readings would involve the utilization of a pressure mat, specifically the 114 Pressure Sensor Tex 03 (Fig. 9). This specific model was chosen as it was the most economical based on the adequate size (360 by 30 mm) to contain a seated person with its sensor spots arranged in a 16 X 16 position (diameter of 10 mm) at a resolution of 20 mm from centre (Fig. 10) This mat would suffice in giving a precise and accurate pressure reading and its flexible property was advantageous in conforming neatly over the contours of the seat.

Once the mat was properly set up, it was then connected via 2 x 16 connector pins into the desktop, where the colours representing the pressure magnitude were mapped onto the computer screen⁹. The compiled data would then be retrieved from real time digital output in an excel file, in which the readings depend significantly on the stature of the user. Theoretically, a heavier user would generate a higher pressure value as compared to the lighter user and vice versa¹⁰.

The athlete's attribute of maximum reach and reaction timing was determined earlier in the project, and those two tests were put into a similar use here.

Figure 9. 114 Pressure Sensor Tex 03

Figure 10. Pressure Mat Sensor Layout (Note: Test was done on the underside of the pressure mat (Flipped over))

Pressure Conversion

The values which are generated in comma-separated-values (csv) format are the electronic values which have to be converted to pressure readings (Pascal). To achieve that, lab weights were used to generate the readings on four specific sensor spots (Fig. 11). This process was done thrice with the same weight, starting from 0.5 kg, for result reliability. Thereafter, the mass loadings were slowly increased by an additional 0.5 kg at each repetition, until the electronic results gave a maximum allowable reading of 4095 with a load of 6 kg. To derive the approximate pressure, the formula (Pressure = Force/Area) was used. The area of contact would be constant throughout the test, with the lab weight holder having a circular base diameter of 0.022 m, thus giving an area of 0.00038 m². The force derived would simply be multiplication of the mass of lab weights by gravitational force. From these values, the average reading was taken for each repetition in order to plot a graph of the electronic values versus the calculated pressures (Fig. 12). The plotted measured values were compared to the supplier's formula ($y=2E-22x^5 - 1E-16x^4 + 3E-11x^3 - 3E-6x^2 + 0.1665x - 9.5273$) for the relationship between the electronic values and pressures, which showed a good match.

Figure 11. Pressure Conversion Setup (Addition of Lab Weights)

Figure 12. Graph relation for the conversion between pressure and electronic values

Maximum reach test

The maximum reach test setup would be similar to the player profiling done for the data collection from the maximum sweep test with the only difference being the additional implementation of the pressure mat (Fig 13). The test user was seated 0.3 m away from the edge of the table and the pressure mat was secured onto the seat to capture the infrared images of the Gluteus Maximus and hamstring muscles. He subsequently executed the motion in three repetitions to obtain better result reliability.

Figure 13. Pressure Test Setup

Methods for interface pressure analysis

A pressure mat is commonly used to evaluate the sitting behavior and amount of force applied on the surface for any test subject. Since the readings and data produced by most of the pressure mat can be interpreted accurately by its own program, this is the only way to produce acceptable pressure distribution results¹¹. Additionally, being able to conduct the experiment safely and understanding how the pressure distribution might affect a real-life human is also important. By having the design of the pressure mat implemented according to the biomedical field standards for evaluation, a benchmarking of pressure mapping pattern must clearly be identified. Furthermore, the human physical and

cognitive factors must also be accounted for. The physical factors include weight, height and profiles, while the cognitive factors include memory, response and reflexes. A more in depth study could account for the variability in these factors from subject to subject. Due to the fact that it is difficult to identify both subjects with similar factors, it would be wiser to design the study to fit some percentile of the population to decrease the influence of individual variability.

The main methods for interface pressure distribution in biomedical evaluation can be divided into three categories: simple benchmarking, statistical analysis and pattern recognition tools.

Simple benchmarking

A number of different parameters can be used to compare the pressure distribution pattern on the surface or subject. Having a simple benchmark for the comparison can greatly simplify the process. With various publishers publishing different benchmarking methods, it is very difficult to make a full comparison. The most commonly used parameters usually include the pressure that is acted on the surface, quality of pressure distribution, high concentrated pressure area and some other specific analytical parameters for specific purposes¹²⁻¹⁵. In the report written by Reed and Lehto¹⁶, quantitative metrics were used for their analysis on the pressure distribution with human subjects. They faced some challenges when gathering data from a seat-based occupant classification system, which is only recommended when the pressure distribution related parameters are contrasted with seat weight sensor data. However, the experiment does have its limitation and it is sensitive to random errors¹⁷.

Statistical Analysis

Researchers suggest that by using statistical tools as their approach for statistical analysis, a better illustration for the pressure distribution from the measured data may result. The approach used by Shelton et al.¹⁵ in the published article used pressure index, $P_{index} = \sqrt{((\mu_{10} - 10)^2 + \sigma_{10}^2)}$, where μ_{10} is the mean of 10 samples and σ_{10} is the standard deviation over 10 samples, as their equation for evaluating performance of the different medical support surfaces. On the other hand, Eitzen¹⁸ used the method of frequency analysis approach to compute the differences between three soft surfaces¹⁸. With this approach, Eitzen was able to prove the variation of result among the surfaces, which Shelton et al. were unable to do. In summary, statistical analysis results vary depending on the method used.

Calibrating the pressure mat

The results of the preliminary evaluation of the pressure mat are presented, which consist of statistical data from the electronic values from the mat. With these data, the pressure mat pressure distribution measurements were justified in being used in the quantitative evaluation of the change in the athlete's performance when using the modified wheelchair. A human test participant was tasked to sit on the pressure mat and execute a series of movements. The mean of electronic readings from the pressure mat over the 256 sensor nodes were computed. Each type of action sequence was repeated three times, and the mean and standard deviations of the mean pressure readings of these trials were obtained. Three types of action sequences were executed: still, backward, forward as

shown in Fig. 14, still, right, left as shown in Fig. 15, and still, small movements as shown in Fig. 16. The data are presented in two fields, left and right, which refer to the pressure readings over the left and right Gluteus Maximus. Table 2 shows the statistics of the normalized mean and standard deviation of the pressure readings over the execution of the action sequences. The smallest of the standard deviations (1% of maximum reading) occurred during the execution of small movements or fidgeting by the participant. Much larger deviations of the pressure readings were expected during game play, since larger movements with greater forces will be performed. As such, it is assumed that the pressure mat had sufficient sensitivity and resolution for the quantitative evaluation of the state of performance and comfort of the athlete.

Figure 14. Normalized mean pressure electronic readings from the test sequence – still, backward, forward

Figure 15. Normalized mean pressure electronic readings from the test sequence – still, right, left

Figure 16. Normalized mean pressure electronic readings from the test sequence – still, small movements

Table 2. Statistics of normalized mean electronic pressure readings for three different action sequences

Normalized Pressure Values	Still, Backward, Forward	Still, Right, Left	Still, Small Movements
Left Mean	0.92	0.88	0.99
Left Standard Deviation	0.04	0.13	0.01
Right Mean	0.94	0.79	0.99
Right Standard Deviation	0.02	0.19	0.01

Results

This section will discuss the performance of Class 1 and Class 2 athletes after the improvements were made. In addition, a reach and sweep time test was repeated by both athletes to compare with the previous results.

Sweep area test results

The handle grip design consisted of three components; handleslot (A), anchor (B) and the fastener loop (C). The handleslot provided a means of insertion into the push handle of the wheelchair. The anchor was meant to secure the athlete's arm to prevent him from falling over, while the fastener loop allowed the entire product to be fastened onto the wheelchair via a cable to prevent excessive shifting of the handle grip once it had been secured. Once the handleslot was fabricated as shown in Fig. 17, the anchor and fastener loop were then permanently assembled together by arc welding. Lastly, a cushioning sleeve was slotted over the anchor to provide an additional means of comfort for the athlete.

Figure 17. Handle grip assembly

Testing was done on the athletes with constant feedback and fine adjustment. For the Class 1 athlete, the introduction of the handle grip was immediately accompanied by

comfortable posture and ease of use. On the other hand, the Class 2 athlete needed some adjustments to his new belt constraint. After several attempts, he gained enough confidence to lean forward more and reach out for the ball. Overall, the improvement was significant as shown in the Table 3. The sweep area of the Class 1 athlete increased by 11.7% when he performed the sweep area test while seated in the wheelchair with the newly installed handle grip assembly. This assembly allowed him to extend further forward than he could when he used the wheelchair with the old handle grip. Also, the Class 2 athlete was able to achieve an increase of 94% in sweep area when he used the newly designed velcro harness with bungee cord, compared to that achieved when he used the standard one-piece elastic strap.

Table 3. Overall improvement of Class 1 and Class 2 athletes in terms of sweep areas (SA)

Equipment Type	Sweep Area (mm ²)
Class 1 athlete with original push handle bar	715,750
Class 1 athlete with new handle grip assembly	799,512 (increase of 11.7%)
Class 2 athlete with original strap constraint	620,375
Class 2 athlete with new velcro harness with bungee cord constraint	1,203,788 (increase of 94.0%)

Figure 18. (Left) Class 1 athlete's original awkward position while playing; (Right) An increase in SA with the addition of the handle grip assembly

Conclusion

According to the athlete's feedback, a definite improvement was experienced in terms of comfort and stability after modifications to the wheelchair handle were made. His body movements were less restrained, aided by the forward positioning of the anchor, enabling him to have a further reach than before. The elastic harness benefitted the Class 2 athlete by giving him more confidence in reaching for a serve. Furthermore, the harness enabled the player to reach for near-net balls with consistency without compromising on safety. Although only three main player's performance factors were studied, other contributing factors may affect performance including arm length, a higher wrist, and elbow strength. There is an exceptional case where a player is able to improve his range of reach and tipping angle by wearing a chest strap as a safety device.

The pressure deviations, obtained from the static posture test, ranged from 0.62% to 2.77% for the left limb, while those for the right limb ranged from 0.73% to 3.33%. The resolution of the pressure sensor mat was suitable for detecting minute, fidgeting motions of the player, thus highlighting the potential of it to be used to observe signs of discomfort or variation in confidence levels during game play. The results from the pressure mats will enable coaches and seat designers to optimize conditions for the players to achieve higher levels of confidence and resilience during game play.

This study provides an overview of the current problems faced by athletes playing para table tennis, and offer solutions that enable them to increase their individual performance. A series of methods for testing the athlete's performance provides the team's coach with quantitative results on the ability of para table tennis players. The methods presented in this report also allow other coaches in the team to be able to replicate the test accurately and interpret the results easily and systematically.

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