FABRICATION AND RULA ANALYSIS OF HAND-ARM REHABILITATION TRAINER FOR CHILDREN SUFFERING FROM CEREBRAL PALSY

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ABSTRACT

Cerebral palsy (CP) is a condition that affects a person's mobility, muscle tone, and posture, resulting in disability. Individuals with CP often require the assistance of a caregiver to carry out their daily activities. Hence, strengthening their hands through exercise is critical in increasing voluntary control. A hand-arm trainer is a tool that provides assistive training for CP patients during therapy to strengthen their hands. It improves motor skills, particularly in the forearm and wrist areas, because one of the most important functions of the limbs is the ability of the hands to grab and hold objects. This study was conducted to develop a hand-arm trainer for children with CP aged six to twelve years old who have Gross Motor Function Classification System (GMFCS) Level III and IV. The outstanding design was selected based on the highest score. Using the Pugh Concept Selection Method, Design 2 was chosen because it received the highest-ranking score compared to the other two designs. According to SOLIDWORKS simulation results, the maximum stress for Design 2 is 19.845 x 10^7 N/m^2, while the maximum yield stress is 22.059 x 10^7 N/m^2. The selected raw materials for Design 2 cost approximately RM 49.30 and weigh 5.438 kg. Adjustable height, adjustable resistance, and ease of maintenance are just a few features of the chosen hand-arm trainer in fabricated Design 2. The level of risk of disorder using Rapid Upper Limb Assessment (RULA) was conducted in accordance with the anthropometric dimensions of children under 12 years old. The detailed design of manikin posture is modelled and analysed. A RULA score of 3 was obtained, indicating that the person is working in a posture that could present some risk of injury from their work posture. Therefore, a change in work posture may be necessary to avoid the risk of injury.

Keywords: *Cerebral palsy, hand-arm trainer, Solidworks; RULA, rehabilitation.*

1.0 INTRODUCTION

Cerebral palsy (CP) is a neurological illness that impairs muscular movement and coordination due to brain injury or impaired brain growth during the fetal period, resulting in motor impairments and uncontrollable tremors in children diagnosed at two years or older [1]. It is the most common physical disability among children [2]. The prevalence of CP ranges from 1.5 to 4 cases per 1,000 live births [3, 4]. CP is a permanent condition that affects movement, balance, posture and necessitates long-term rehabilitation. Children with CP have limitations in moving their limbs, such as their hands and legs, for daily activities and require assistance from caregivers to perform activities or move from one place to another, depending on their level of gross motor skills. Different classification systems known as Gross Motor Function Classification System (GMFCS) are used for the categorization of CP based on a functional basis, consisting of Level 1 until Level IV.

Muscle from CP patients are shorter and smaller, with decreased fiber diameter, sarcomeres twice decent length (and thus fewer in number), hypertrophied extracellular matrix, immature myosin, and up to 70% fewer satellite cells [5]. These elements interact to cause tight and weak muscle. Appropriate therapy should be implemented to ensure that muscles work in accordance with the growth of the surrounding bones. Exercising a disabled limb improves upper limb function in children with CP, which can lead to enhanced routine performance, social integration, and, ultimately, a higher quality of life [6-8].

Hands play an important role in CP patients' daily and social activities. Good use of their hands can significantly impact their ability to perform tasks independently, making tasks easier compared to those who cannot fully use their hands due to weak or less effective grips. As a result, intensive and efficient training is required to improve their grip strength and arm muscle strength. Hand-arm intensive bimanual therapy (HABIT) is a type of bimanual intervention demonstrated to effectively enhance upper-extremity function [9]. HABIT emphasized the coordination of both arms through structured tasks in bimanual play and daily activities [10]. Few studies have assessed the effectiveness of intensive HABIT rehabilitation in young children. Ouyang *et al.* [11] reported that a HABIT regimen consisting of 6 hours per day for three consecutive weeks resulted in improvements in bimanual ability, unilateral dexterity, self-care functions and achievement of functional goals. These improvements were largely sustained during the follow-up period. In another study, Sara Samir Mohamed *et al.* [12] recommended physical therapy interventions involving HABIT for 6 hours a day over a period of 15 days.

One approach to assist CP patients in managing their excessively tight muscles involves using a hand-arm trainer to enhance their hand strength, allowing them to hold objects more easily. This assistive tool resembles a bike, however, it incorporates handles for the hands. The motor abilities, especially in the forearm and wrist areas is crucial as the primary function of the limbs is the ability to grasp and hold objects. Although hand-arm trainer come in a variety of shapes and sizes, the availability of a hand-arm trainer is extremely limited. They must be ordered in advance from the manufacturer. Despite their benefits in providing effective physical therapy and improving the quality life for children with CP, the high cost and weight can limit their accessibility and practicality for everyday use. For instance, Tzora Rehabilitation Centre manufactures hand-arm trainers that can move themselves automatically, also known as active movement, and sells them for RM 12,139.00 with the weight of 11 kg [13]. The weight plays an important role in ensuring that the hand-arm trainer remains stable, especially during intensive training. Meanwhile, the passive mode trainers are designed to be small and lightweight (approximately 3 kg), facilitating easy portability [14]. Addressing these accessibility issues is crucial to ensure that children with CP can benefit from this rehabilitation equipment.

In this study, CP children aged six to twelve years old with GMFCS focusing on Level III and Level IV, wherein children walk with the aid of a hand-held mobility device or require physical assistance in most situation, respectively, is emphasized. Three concept designs (Design 1, Design 2 and Design 3) of the hand-arm trainer were sketched using SOLIDWORKS software. The design with the highest score on the Pugh Chart is chosen for fabrication. The design criteria for the hand-arm trainers include performance, cost, and weight. Rapid Upper Limb Assessment (RULA), which simulates an analysis of user comfort was conducted using CATIA to consider the ergonomic score.

2.0 METHODOLOGY

2.1 Design Criteria

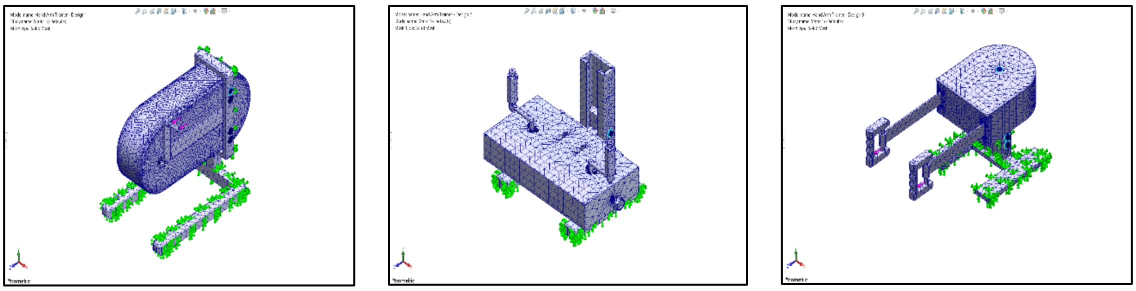
The specific requirements that a design must meet to achieve its primary goals are referred to as design criteria. Several criteria for designing the hand-arm trainer were defined, as shown in Table 1.

Table 1: Design criteria of hand-arm trainer

Criteria	Description
Functional	Provide intensive training for children with CP who are classified under Gross Motor Function Classification System (GMFCS) of Level III and IV, who needed physical assistant. Frequent movement repetition should be included.
Comfortability	The handle is designed to accommodate the fingers of children with CP and enhance hand functionality, enabling them to work together in coordination.
Maintainability	The handle is detachable, making it easy to store and maintain.
Safety	The broad base of the assistive tool prevents toppling while operating the hand-arm trainer. Every sharp edge of the hand-arm trainer must be blunted to avoid injury to children with CP.

2.2 Structural Analysis

For each design, an analysis must be performed using appropriate structural models that account for the influence of all relevant variables. To conduct the structural analysis, an appropriate mathematical model must be used to idealise both the structure's shape as well as the actions and support conditions. Additionally, the modulus conditions of the cross-sections, members, joints, and ground interaction must be approximated. When second-order effects significantly amplify the effects of the actions, the simulations must account for the effects of movements and deformations in such structures or portions thereof. In this simulation, mild steel and stainless steel 304 were used as the respective raw materials for Designs 1, Design 2, and Design 3. To ensure that the design does not fail during use by CP children aged six to twelve years old, the load exerted by pushing forward with their hand on the handle is subjected to a maximum force of 70 N, which is approximately 7.138 kg, as reported by Division of Manufacturing Engineering and Operations Management, University of Nottingham [15]. In order to carry out the analysis, the structural models of Design 1, Design 2 and Design 3 must first be meshed to ensure accurate results based on the dimensions and characteristics of the geometry as shown in Figure 1.



a) b) c)

Figure 1: Solid mesh of a) Design 1, b) Design 2, and c) Design 3

Simulation of stress-strain analysis, often known as stress analysis, employs a technique used to identify the stresses and strains that forces on materials and structures cause. As shown in Figure 2, Design 2 can withstand the most stress when operated by the load of 70 N with the result of 15.181 x 10^7 N/m^2 compared to its competitors which are 3.921 x 10^7 N/m^2 and 1.516 x 10^7 N/m^2 for Design 1 and Design 3, respectively.

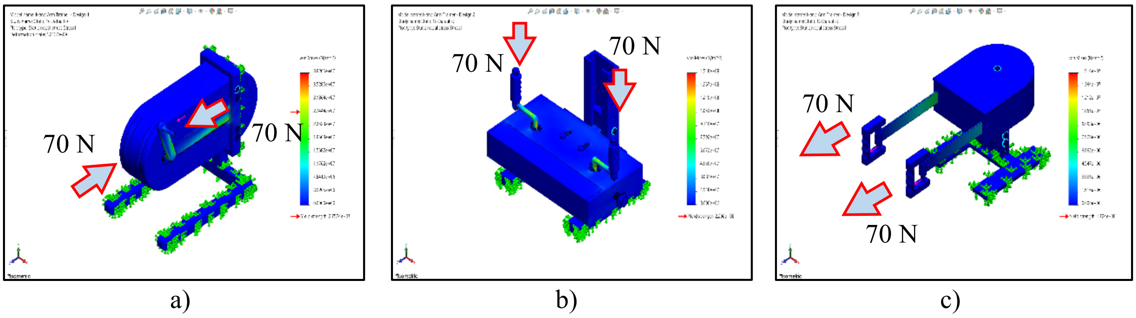


Figure 2 : Maximum yield stress analysis (Von Mises) of a) Design 1, b) Design 2, and c) Design 3

The factor of safety (FOS) is a critical measure that indicates the degree to which a structure is stronger than required to support the intended load. It is calculated as the ratio of acceptable stress to actual stress as shown in Figure 3. In Design 2, the FOS is 1.45, meaning that the stress is within the permissible range since it is greater than 1. In contrast, Design 1 and Design 3 have FOS of 0.7 and 0.41 respectively, suggesting a higher likelihood of failure as their values are less than 1. Thus, Design 2 is the safest option.

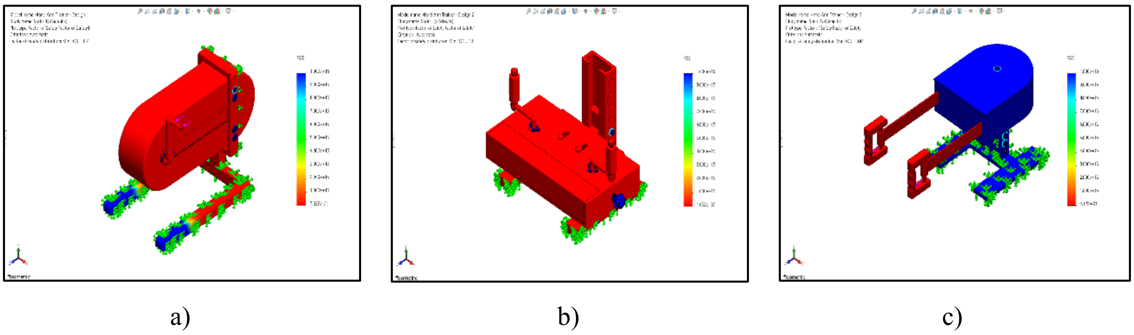
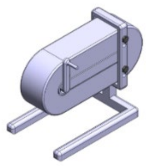
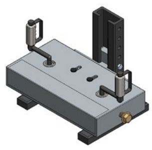
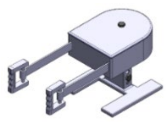


Figure 3: Factor of safety of a) Design 1, b) Design 2, and c) Design 3

2.3 Pugh Chart

A Pugh Chart is a simple planning tool for comparing design concepts to design objectives early in the design process, as shown in Table 2.

Table 2: Design selection attributes

Design Selection Attributes		**Design 1** 	**Design 2** 	**Design 3** 
Performance	Maximum stress (Von-misses) (N/m^2)	3.921×10^7	19.845×10^7	1.516×10^7
	Maximum yield stress (N/m^2)	2.757×10^7	22.059×10^7	17.240×10^7
	Factor of safety	0.70	1.45	0.41
Weight	Mass (kg)	4.936	5.438	2.530
	Volume (mm^3)	0.484×10^7	0.544×10^7	0.253×10^7
Cost	Raw material cost (RM)	RM 14.70 per kg 4.936 kg = **RM 72.56**	RM 9.06 per kg 5.438 kg = **RM 49.30**	RM 13.90 per kg 2.530 kg = **RM 35.17**

The design that best satisfies each criterion's objective is chosen using the Pugh Chart scoring criteria. This study takes into account performance, weight and cost. As shown in Table 3, the scale is defined as (+) for better, (-) for worse, and (0) for equal. If one design dominates the others by having more (+) scores, the decision is made easier, and the chosen design moves forward with the fabrication process. Design 2 dominates the Pugh Chart due to its high maximum stress and yield strength. A safety factor value greater than one indicates that the design is in good condition and safe according to the material used to create the design. For weight selection, a hand-arm trainer should be heavier to ensure stability when used on a table by children with CP. A heavier trainer prevents flipping and swaying while in use, reducing the risk of harm to the user, such as falling. As for the price of raw materials, Design 3 had the lowest estimated value compared to the other two designs.

Table 3: Pugh Chart

Concepts Variants				
Characteristics		**Design 1**	**Design 2**	**Design 3**
Performance	Maximum stress (Von-misses) (N/m^2)	-	+	-
	Maximum yield stress (N/m^2)	-	+	-
	Factor of safety	-	+	-
Weight	Mass (kg)	+	+	-
	Volume (mm^3)	+	+	-
Cost	Raw material cost (RM)	-	-	+

Based on the Pugh Chart, all designs were evaluated and given points based on the total number of symbols successfully collected. This determines whether the design can be further developed for fabrication. Design 2 was selected based on its qualifications and the highest number of points collected when compared to its competitors, as shown in Table 4.

Table 4: Ranking of the design

Characteristics	**Design 1**	**Design 2**	**Design 3**
Sum '+'	2	5	1
Sum '0'	0	0	0
Sum '-'	4	1	5
Net score	-2	4	-4
Rank	2	1	3
Continue?	No	Yes	No

2.4 Rapid Upper Limb Assesment (RULA)

Considering the users' working posture, which mainly involves arm and shoulder movements when operating the hand-arm trainer, Rapid Upper Limb Assesment (RULA) analysis was chosen for this investigation. Focusing on the neck, trunk, and upper limbs, the RULA approach measures a subject's exposure to postures, pressures, and muscle activities that can lead to repetitive strain injuries. The final RULA score for the posture was determined using CATIA.

3.0 RESULTS AND DISCUSSION

The hand-arm trainer was designed to assist children with CP in performing hand exercises more effectively. Design 2 was selected and the specifications used in the fabrication of this hand-arm trainer are listed in Table 5.

Table 5: Specifications of fabricated hand-arm trainer (Design 2)

Specifications	Details
Material	Mild steel, stainless steel 304
Size	450 mm (length) x 330 mm (height) x 300 mm (width)
Features	i. Adjustable height
	ii. Adjustable resistance
	iii. Easy maintenance

3.1 Adjustable Height

The adjustable height is a major draw factor, as it is deemed suitable for use by CP children, who may vary in height despite their similar age range. The hand-arm trainer casing can be raised and lowered to facilitate usage according to a child's hand level. This hand-arm trainer can be adjusted to a maximum height of 308 mm and a minimum height of 188 mm from the ground floor, as shown in Figure 4. The height of approximately 300 mm is suitable when the user is in a seated position on the floor, as the sitting shoulder length for children aged between six and twelve is approximately 417.45 mm [16].

a)

b)

Figure 4: Hand-arm trainer at: a) 188 mm from the base, and b) 308 mm from the base

3.2 Adjustable Resistance

The hand-arm trainer is equipped with a rubber pad to provide resistance to the pulley, as shown in Figure 5. The resistance can be increased by applying slight pressure to the section of the rope that is in contact with the pulley by turning the nut. This adjustment is beneficial for children who find the current rotation insufficiently challenging or have already mastered it. When the pulley belt tightens, the amount of force needed to complete a full rotation increase. Hence, by gradually increasing the resistance, the user can engage in more intense training to further strengthening the hand muscle.

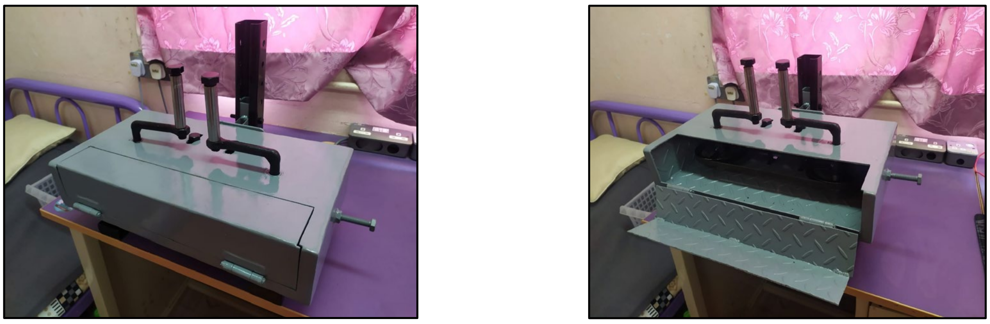
a)

b)

Figure 5: a) No resistance as the brake pad is not touching the belt, and b) Brake pad touching the belt to provide some resistance

3.3 Easy to Maintain

An opening lid resembling a window at the front of the casing was created to provide access for maintenance and repairs in the event of unforeseen issues such as a broken belt, internal damage, or malfunctioning pulleys, as shown in Figure 6. Initially, the lid opened from the top, but concerns arose regarding the potential collusions between the lid and the handle when opened to replace belts or perform other tasks. Therefore, after careful consideration, the lid was modified to open from the bottom.

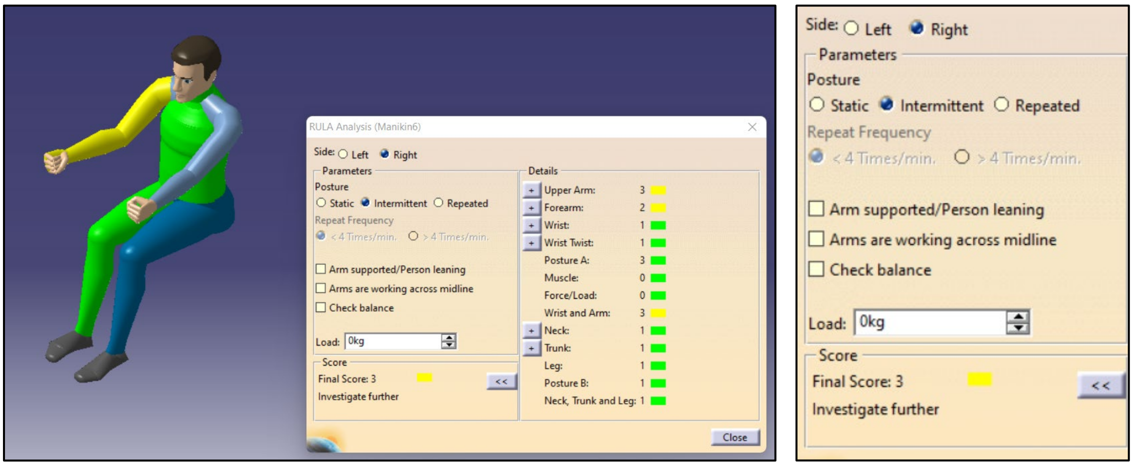


a) b)

Figure 6: Easy Maintainability*:* a) Close lid, and b) Open lid

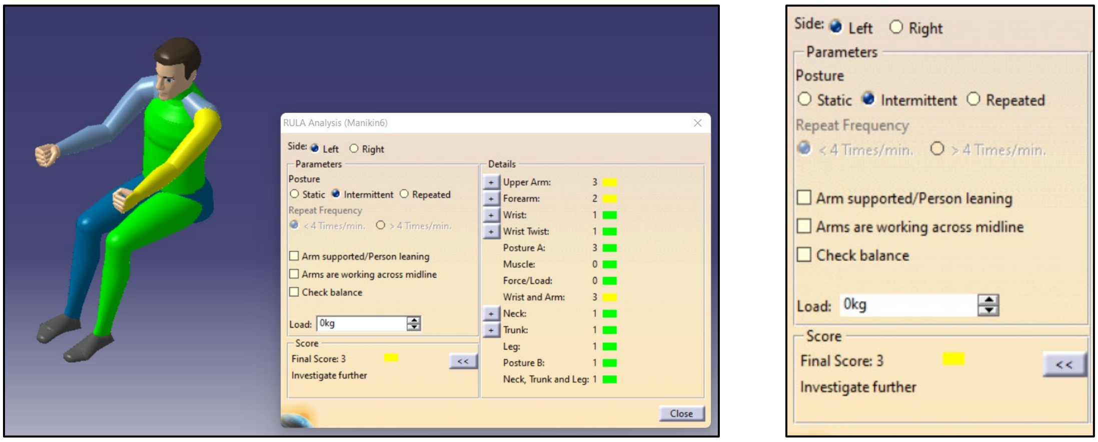
3.4 RULA Score

RULA analysis are recorded on two sides, left and right. Figure 7 shows the scoring of the right side of the manikin using CATIA, with high values observed on the upper arm, as well as wrist and arm, marked with yellow markers, scoring 3, and 3 respectively. As shown in Figure 8, the same scoring pattern is observed on the left side, resulting in a final score of 3.



a) b)

Figure 7: Scoring of right-side manikin with: a) Details score, and b) Final score



a) b)

Figure 8: Scoring of left-side manikin with: a) Details score, and b) Final score

4.0 CONCLUSION

The performance, weight, and cost of Design 1, Design 2 and Design 3 were compared in fabricating the hand-arm trainer. Design 2, which received the highest score in the Pugh Concept Selection Method's, was selected to proceed to the fabrication phase. The hand-arm trainer was designed with the pulleys placed horizontally to facilitate a pedaling motion similar to cycling. This positioning allows for a parallel level between the two pulleys, suitable for rehabilitation and training of the hand and upper extremities. Based on the RULA analysis, the manikin's posture received a final score of 3, indicating that it is acceptable but requires modifications.

For future research, the pulley used as a driving mechanism in the hand-arm trainer could be replaced with a gear that provides direct contact between the two handles, unlike a pulley using a V-belt strap which may sometimes experience slight slipping during rotation. Apart from that, the mechanism used to adjust the height of this prototype can be improved by implementing a rack and pinion system or crank mechanism. With this improvement, adjusting the height will become easier without the need for additional hand tools to remove bolts and nuts.

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REFERENCES

1. Paul S., Nahar A., Bhagawati M. and Kunwar A. J. 2022. A review on recent advances of cerebral palsy. *Oxidative Medicine and Cellular Longevity*, 2022: 1-20.
2. Araneda R., Ebner-Karestinos D., Paradis J., Klöcker A., Saussez G., Demas J., Bailly R., Bouvier S., Carton de Tournai A., Herman E., Souki A., Le-Gal G., Nowak E., Sizonenko S. V., Newman C. J., Dinomais M., Riquelme I., Guzzetta A., Brochard S., Bleyenheuft Y., 2024. Changes induced by early hand-arm bimanual intensive therapy including lower extremities in young children with unilateral cerebral palsy: A randomized clinical trial. *JAMA Pediatrics*, 178: 1-10.
3. Patel D.R., Neelakantan M., Pandher K. and Merrick J. 2020. Cerebral palsy in children: A clinical overview. *Translational Pediatrics*, 9: 125-135.
4. McIntyre S., Goldsmith S., Webb A., Ehlinger V., Hollung S. J., McConnell K., Arnaud C., Smithers-Sheedy H., Oskoui M., Khandaker G. and Himmelmann K. 2022. Global prevalence of cerebral palsy: A systematic analysis, *Developmental Medicine & Child Neurology*, 64(12): 1494-1506.
5. Pfeifer, L. I., Silve D. B. R., Funayama C. A. R. and Santos J. L. 2009. Classification of cerebral palsy: Association between gender, age, motor type, topography and gross motor function. *Arquivos De Neuro-Psiquiatria,* 67(4): 1057-1061.
6. Arpino C., Vescio M. F., De Luca A. and Curatolo P. 2010. Efficacy of intensive versus nonintensive physiotherapy in children with cerebral palsy: A meta-analysis. *International Journal of Rehabilitation Research*, 33(2): 165-171.
7. Baker A., Niles N., Kysh L. and, Sargent B. 2022. Effect of motor intervention for infants and toddlers with cerebral palsy: A systematic review and meta-analysis. *Pediatric Physical Therapy*, 34(3): 297-307.
8. Damiano D. L. and Longo E. 2021. Early intervention evidence for infants with or at risk for cerebral palsy: An overview of systematic reviews. *Developmental Medicine & Child Neurology*, 63(7): 771-784.
9. Alahmari K., Tedla J. S., Sangadala D. R., Mukherjee D., Reddy R. S., Bairapareddy K. C. and Kandakurti P. K. 2020. Effectiveness of hand-arm bimanual intensive therapy on hand function among children with unilateral spastic cerebral palsy: A meta-analysis. *Neurology and Neuroscience,* 83(2): 131-137.
10. Samreen J., Chauhan N., Alam S., Fatima A. and Sahiba, S. 2022. Effect of hand arm bimanual intensive therapy (HABIT) on gross motor functions in upper extremity of spastic CP. *International Journal of Health Sciences*, 6(S4): 3287–3306.
11. Ouyang R.-G., Yang C.-N., Qu Y.-L., Koduri M. P. and Chieng C.-W. 2020. Effectiveness of hand-arm bimanual intensive training on upper extremity function in children with cerebral palsy: A systematic review. *European Journal of Paediatric Neurology*, 25: 17-28.
12. Mohamed S. S., Ghany W. A. A. and Abdelazeim F. H. 2022. Upper limb physical therapy interventions to improve functions in cerebral palsy children: A review article. *International Journal of Health Sciences,* 6(S5): 6545–6560.
13. Active Passive Trainer, 2024. https://www.tzora.com/apt/
14. Niedzwecki, C. M., Thomas S. P. and Schwabe A.L. 2021. Cerebral palsy. *Braddom's Physical Medicine and Rehabilitation (Sixth Edition)*, 1006-1026.

15. Rahmawati, I., Dewi R., Pertami S. B., Buidono and Pasaribu E. 2021. Hand exercise using a rubber ball increases grip strength in patients with non-haemorrhagic stroke. *The Malaysian Journal of Nursing*, 12(3): 1-5.
16. Kabilmiharbi, N. and Selamat, F. E. 2016. RULA analysis of work-related musculoskeletal disorder among polypropylene fibrillated yarn industry worker using digital human modelling (DHM). *Malaysian Journal of Public Health Medicine*, 1: 53-60.