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Usability and Performance Evaluation of a Locally Developed Counterbalance Arm Sling for Hemiparesis Rehabilitation

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ABSTRACT

This study reports the usability and performance evaluation of a mobile, detachable counterbalance arm sling (CBAS) designed to support upper-limb rehabilitation for people with hemiparesis. The device targets key clinical goals of shoulder stabilization, range-of-motion (ROM) support, and reduced therapist burden while remaining low-cost and locally manufacturable. A structured evaluation at a rehabilitation center engaged physiotherapists and a stroke survivor, using a three-part instrument including product rating, performance scale, and recommendation or comments. Respondents rated the CBAS from good to very good across eight usability criteria contains the ease of use, comfort, style, lightweight, functionality, ROM improvement, safety, ergonomics. 25% of the respondents rated performance superior and the remainder acceptable, with 100% recommending continued use. Findings align with contemporary evidence that weight-supporting/mobile arm support can foster arm activity and functional training in hemiparesis, and that usability-first design is crucial for adoption and adherence in real-world rehab. The CBAS demonstrates clinical promise and a path to scalable local production.

Keywords: hemiparesis, arm support, counterbalance sling, usability, rehabilitation engineering.

INTRODUCTION

Stroke-related hemiparesis is one of the leading causes of long-term disability, often resulting in impaired upper-limb mobility and reduced independence [1]. This upper-limb impairment after stroke limits autonomy and participation. Conventional rehabilitation devices frequently rely on imported, high-cost systems that are unsuitable for low-resource clinical settings. Consequently, locally engineered assistive mechanisms, such as counterbalanced arm supports, can play an important role in improving rehabilitation accessibility [2]. Recent usability studies in stroke technology show that safe, motivating, and feasible designs improve uptake, while practical challenges can hinder use if not addressed early. In parallel, mobile arm supports and counterbalance mechanisms aim to compensate limb weight and enable practice with reduced effort; controlled trials and cohort studies suggest weight-supported arm training with computerized or task-specific exercise can produce meaningful improvements in function and capacity. For shoulder subluxation, evidence on slings is mixed: some RCTs report biomechanical benefit (increased acromiohumeral distance, pain/ROM effects) for selected designs, while others show no superiority among common sling types which underscoring that design details and clinical context matter.

Fig. 1 Counterbalance Arm Sling (CBAS) prototype mounted on a standard wheelchair, showing the 3D-printed structural components, arm cradle, counterbalance mechanism, and adjustable support elements.

The Counterbalance Arm Sling (CBAS), shown in Figure 1, was developed to provide mechanical arm support that reduces therapist burden and encourages repetitive, self-initiated upper-limb movement.The Counterbalance Arm Sling (CBAS) was proposed to provide mechanical arm support that reduces therapist burden and encourages repetitive, self-initiated movement among patients.

In addition, the usability and ergonomic assessment are essential to ensure that such devices are effective and acceptable to both clinicians and end-users [3]. In recent years, multiple studies have emphasized integrating human-centred design with biomechanical validation to enhance device performance and user compliance [4], [5]. Evaluating usability in early product stages also reduces rejection rates and informs iterative design improvements [6].

Hence, this study focuses on validating the CBAS through structured usability and performance evaluation, aiming to verify whether the developed prototype satisfies clinical and ergonomic requirements for hemiparetic rehabilitation. This paper evaluates the usability and perceived performance of CBAS. The CBAS intended to assist users in maintaining correct limb posture, reducing shoulder subluxation, and enhancing range of motion through a counterbalanced mechanical system. Incorporating 3D-printed components polylactic acid (PLA) makes it light, affordable, and reproducible locally. This paper focuses on validating the CBAS through usability and performance testing involving real users and therapists in a clinical rehabilitation environment.

The upper limb muscles commonly affected in post-stroke hemiparesis include the deltoid anterior, middle and posterior fibres, biceps brachii, triceps brachii, brachioradialis, wrist flexors, wrist extensors, and gripping muscles. These muscle groups are responsible for shoulder stabilisation, elbow flexion-extension, and distal motor control, all of which significantly influence functional upper-limb performance.

Muscle strength in hemiparetic patients is typically described using the Oxford Muscle Strength Scale (0–5), which ranges from no contraction to full movement against resistance. Understanding the weakness pattern across these muscle groups is essential for interpreting how counterbalance-based devices provide mechanical advantage. In practice, proximal muscles such as the deltoid and biceps benefit most from counterbalanced support due to their difficulty generating anti-gravity force post-stroke. Distal muscles such as wrist flexors, extensors, and gripping muscles often show reduced activation unless proximal stability is achieved.

This context supports the rationale for the CBAS design, which targets proximal unloading to facilitate smoother and more efficient voluntary movement during rehabilitation activities. The muscle groups listed in Table 1 represent the primary proximal and distal muscles commonly weakened in post-stroke hemiparesis and are clinically relevant to upper-limb rehabilitation. Interpreting the functional capabilities of these muscles requires reference to the Oxford Muscle Strength Grading Scale (Table 2), which standardises the assessment of voluntary contraction from 0/5 (no activity) to 5/5 (normal strength).

Table 1. Muscles Involved in Upper-Limb Movement

No.	Muscle Group	Abbreviation	Functional Role
1	Deltoid – anterior fibre	DAF	Shoulder flexion, arm elevation
2	Deltoid – middle fibre	DMF	Shoulder abduction
3	Deltoid – posterior fibre	DPB	Shoulder extension and horizontal abduction
4	Biceps brachii	BB	Elbow flexion, forearm supination
5	Triceps brachii	TB	Elbow extension
6	Brachioradialis	B	Elbow flexion (neutral grip)
7	Wrist flexor group	WF	Wrist flexion
8	Wrist extensor group	WE	Wrist extension
9	Finger/grip muscles	GP	Hand opening/closing, grip strength

Table 2. Oxford Muscle Strength Grading Scale

Grade	Description
0/5	No visible or palpable muscle contraction
1/5	Palpable/visible contraction but no movement
2/5	Movement possible only with gravity eliminated
3/5	Movement possible against gravity only
4/5	Movement against gravity with some resistance
5/5	Movement against gravity with full/normal resistance

By mapping each affected muscle to its corresponding functional role and strength grade, the interaction between proximal weakness and movement limitations becomes clearer. This relationship is crucial for understanding how a counterbalance-based device such as the CBAS can mechanically compensate for reduced anti-gravity strength, particularly in the deltoid and elbow flexor groups, thereby facilitating smoother, more controlled movement during rehabilitation activities.

METHODOLOGY

The CBAS is a passive, counterbalanced arm support mounted to a wheelchair or stand, allowing multi-axis motion with tuned resistance. The CBAS was designed to support upper-limb movement by counterbalancing the weight of the arm, thereby reducing fatigue during exercises. The design incorporated lightweight materials fabricated using fused deposition modelling (FDM) 3D printing to achieve customizable geometry and affordability. Physical product testing was conducted at the Rehabilitation Centre. The design mirrors modern mobile arm supports compensating limb weight to facilitate active practice while maintaining safety and fit for local anthropometry.

Evaluation occurred in a rehabilitation center with three certified physiotherapists (n=3) and one hemiparetic patient post-stroke participant (n=1). All participants participated voluntarily. All participants were seated in a wheelchair equipped with the final CBAS prototype during testing. The evaluation followed a structured product testing protocol with three sections:

1. Product Rating : assessed eight usability criteria (ease of use, comfort, style, lightweight, functionality, improved ROM, safety, ergonomics).
2. Performance Measurement Tool : rated product quality on a five-level scale (very poor to superior).
3. User’s Recommendation and Feedback – collected open-ended opinions and improvement suggestions.

Each participant used the device during a rehabilitation session and subsequently completed the survey form. Descriptive statistical analysis summarized trends in user responses.

RESULTS AND DISCUSSION

Muscle Groups and Strength Considerations

The muscle strength profiling offers valuable insight into how the CBAS facilitates movement across the upper-limb kinetic chain, supporting the clinical relevance of counterbalance-based assistance in early or moderate stages of post-stroke rehabilitation.

As in Figure 2, six respondents demonstrated muscle strength of grade 2/5 and above, indicating the ability to initiate movement against gravity. This level of functional capacity suggests that these individuals are appropriate candidates for passive arm-support devices such as the counterbalance arm sling, which aids in facilitating anti-gravity movement during rehabilitation tasks.

Fig. 2 Muscle strength distribution of the right upper limb

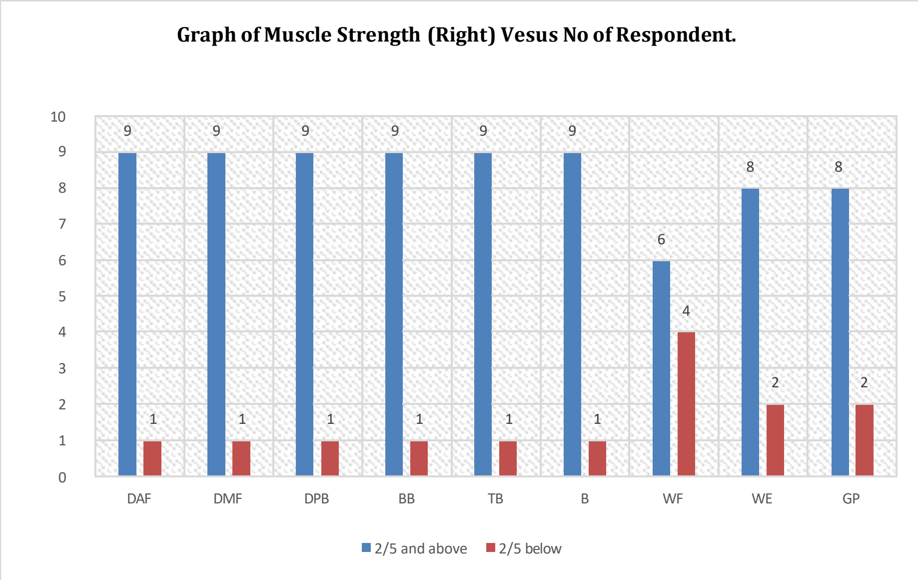


Fig. 3 Muscle strength distribution of the left upper limb

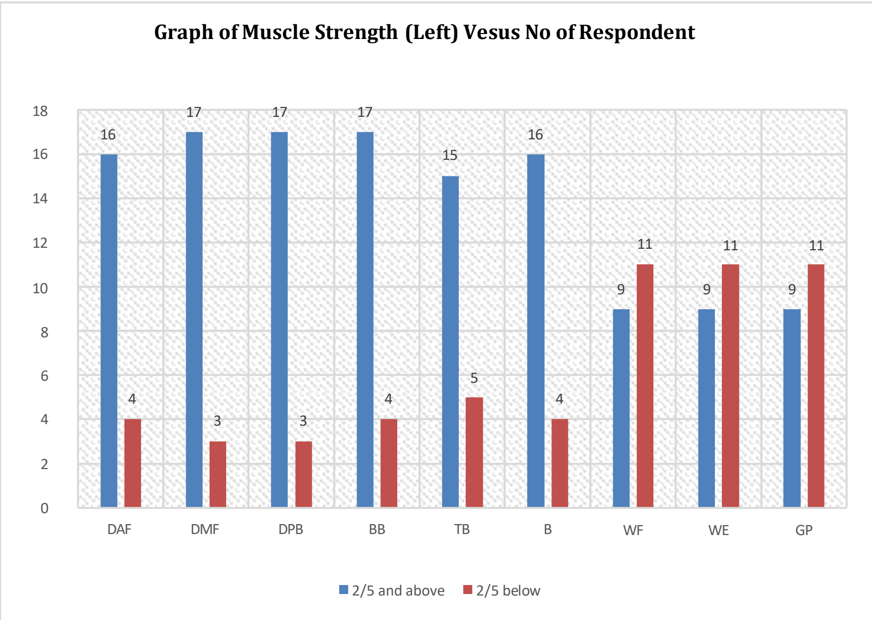


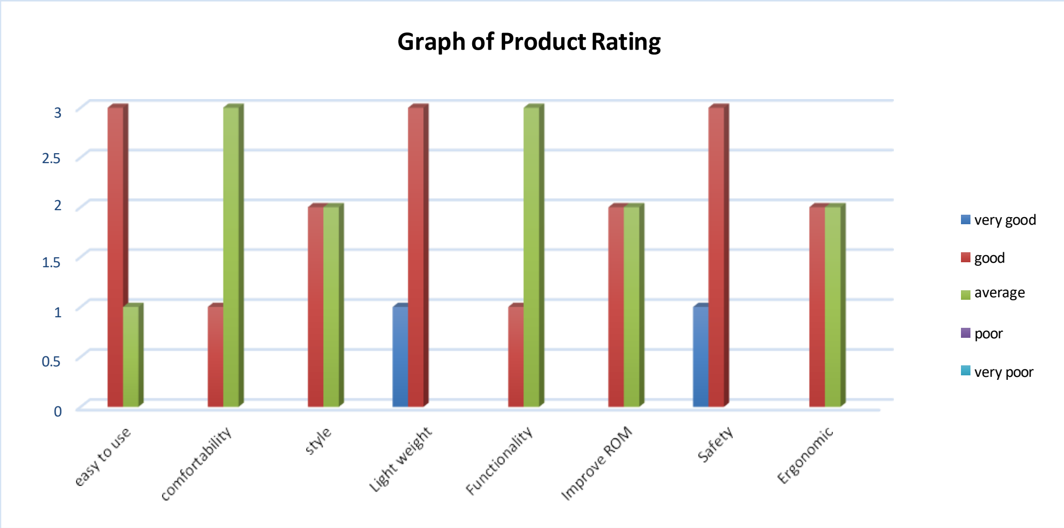
Figure 3 above shows respondent have the muscles strength of 2/5 and above where they can at least have movement against gravity and are recommended to use passive arm support such as counterbalance arm sling.

The muscle strength comparison between the right and left upper limbs revealed that proximal muscles consistently demonstrated higher strength scores (≥2/5) compared to distal muscles. This pattern is expected in post-stroke hemiparesis, where anti-gravity shoulder and elbow muscles recover earlier than wrist and hand muscles. The counterbalance support provided by the CBAS is therefore most beneficial for assisting proximal lifting actions, enabling patients with limited strength to initiate movement against gravity.

Product Rating

The evaluation results in Figure 4 shows that all respondents rated the CBAS between average and very good across all eight design criteria. This indicates strong overall user satisfaction, particularly in comfort, ease of use, and ergonomics, confirming that the design fulfills user-centered objectives. The positive feedback demonstrates that the CBAS provides sufficient mechanical support while maintaining user comfort during upper-limb movements.

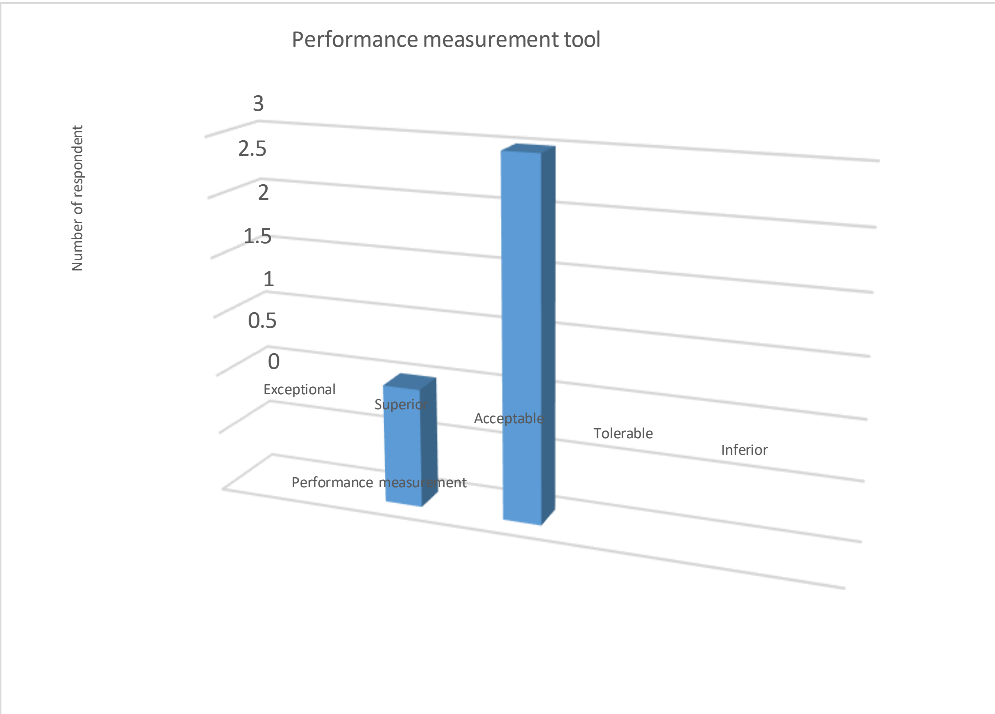
Fig. 4 Product Rating Evaluation of the product



The CBAS's lightweight design further contributed to its positive usability profile. Similar observations have been reported for exoskeletal rehabilitation devices designed with reduced mechanical impedance [9], confirming that minimized weight improves range-of-motion compliance and patient confidence. Comfort, safety, and ease of use received the highest scores, reflecting good ergonomic integration and user-friendly operation. This aligns with findings by Resnik et al. [7] and van der Loos et al. [8], who emphasized comfort and intuitive control as critical determinants of patient adherence in upper-limb assistive devices.

Product Performance

Fig. 5 Product Rating Evaluation of the product



The performance measurement tool as illustrated in Figure 5 above demonstrated that one respondent rated the CBAS as "superior" and three as "acceptable." A "superior" score indicates that the product exceeded expectations in stability and movement smoothness, whereas "acceptable" scores confirm adequate mechanical response and clinical safety. These outcomes suggest that the CBAS prototype meets minimum clinical quality standards and compares favourably with other low-cost rehabilitation supports [10], [11]. Collectively, these outcomes affirm that the device meets professional and patient requirements for effective rehabilitation aids.

User's Recommendation and Feedback

All four respondents recommended that the product continue to be used and improved for wider rehabilitation applications.

Their specific comments included:

1. Therapist 1: The device helps stabilize the patient's shoulder.
2. Therapist 2: Effective for upper-limb strengthening and isolated shoulder–elbow movement training.
3. Therapist 3: Useful in preventing shoulder subluxation.
4. Patient 1: Enables smoother arm movement during exercise.

All respondents unanimously recommended continued use of the Qualitative comments highlighted its contribution to shoulder stabilization, isolated movement training for shoulder and elbow, and prevention of subluxation. The patient reported smoother limb movement and improved comfort during exercise sessions. Such feedback reflects strong clinical usability potential and positive therapeutic transfer, consistent with user-acceptance trends observed in rehabilitation robotics and passive assistive systems [12], [13].These remarks confirm the clinical validity and ergonomic comfort of the CBAS design. The convergence of opinions between therapists and the patient highlights that the product effectively supports therapeutic objectives while maintaining ease of operation.

The convergence of quantitative and qualitative findings substantiates the CBAS as a functionally efficient and ergonomically validated device. The high comfort and safety ratings demonstrate that the counterbalanced design effectively supports upper-limb motion without imposing excessive constraint. The performance data corroborate the functional expectations reported by similar studies focusing on low-cost assistive supports [14]. Moreover, unanimous therapist recommendation underscores its clinical relevance and adaptability within local rehabilitation contexts.

While these findings affirm product feasibility, limitations include the small sample size and the absence of standardized clinical outcome metrics such as the Fugl-Meyer Assessment (FMA-UE) or Action Research Arm Test (ARAT). Future studies should incorporate larger sample populations, kinematic tracking, and long-term usability assessments. Integration of sensor feedback or surface electromyography (sEMG) could further quantify patient progress and facilitate personalized therapy [15].

CONCLUSION

The usability and performance evaluation confirm that the locally developed CBAS prototype fulfills the functional, ergonomic, and safety requirements for hemiparesis rehabilitation. Respondent feedback validates its comfort, ease of use, and therapeutic benefit, while quantitative results demonstrate consistent performance. The device's affordability and local manufacturability make it a viable option for clinical and home-based rehabilitation in resource-limited settings. Future work will focus on biomechanical optimization, multi-patient trials, and integration of real-time monitoring sensors to enhance data-driven rehabilitation strategies.

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