

DEVELOPMENT OF A BIOMECHANICALLY-COMPATIBLE MOBILITY SOLUTION FOR DOGS USING ECO-FRIENDLY MATERIALS AND CAE STRUCTURAL ANALYSIS

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Abstract. This paper presents the conceptual development of a biomechanically-compatible mobility device designed to assist medium-sized dogs with paresis of the hind limbs. The project, conducted within the scope of an undergraduate engineering design course, aimed to produce an affordable, lightweight, and sustainable solution through a structured and iterative design methodology. Four initial design alternatives were systematically evaluated using a weighted decision matrix, based on criteria such as comfort, ease of use, durability, cost, sustainability, flexibility, and aesthetics. The selected concept was further refined through CAD modeling and CAE-based structural analysis using the finite element method (FEM) to assess the mechanical behavior of candidate materials (namely PET, cardboard, bamboo, and silicone). Cardboard emerged as the most suitable material, balancing structural integrity, low cost, and environmental impact. Additional stability analyses were performed to evaluate the system's performance on uneven terrain and under dynamic loading conditions. The study culminated in a detailed 3D model and technical drawings to support the construction of a functional prototype. The results validate the feasibility of designing assistive devices that are both biomechanically effective and environmentally conscious, offering practical benefits to animal welfare while promoting responsible engineering practice.

Keywords: Assistive device, Biomechanics, Sustainable design, Finite Element Analysis, Canine mobility

Resumo. Este artigo apresenta o desenvolvimento conceitual de um dispositivo de mobilidade biomecanicamente compatível, projetado para auxiliar cães de médio porte com paresia dos membros posteriores. O projeto, realizado no contexto de uma disciplina de projeto de engenharia, teve como objetivo propor uma solução leve, de baixo custo e ambientalmente sustentável, utilizando uma metodologia estruturada e iterativa de projeto. Quatro alternativas iniciais foram avaliadas sistematicamente por meio de uma matriz de decisão ponderada, considerando critérios como conforto, facilidade de uso, durabilidade, custo, sustentabilidade, flexibilidade e estética. A alternativa selecionada foi refinada com modelagem em CAD e análises estruturais baseadas no Método dos Elementos Finitos (MEF), utilizadas para avaliar o comportamento mecânico de materiais candidatos (PET, papelão, bambu e silicone). O papelão mostrou-se o material mais apropriado, por equilibrar resistência, leveza e impacto ambiental reduzido. Foram realizadas análises adicionais de estabilidade, considerando uso em terrenos irregulares e perturbações dinâmicas. O estudo resultou em um modelo 3D detalhado e desenhos técnicos para a construção de um protótipo funcional. Os resultados confirmam a viabilidade de desenvolver dispositivos assistivos eficazes do ponto de vista biomecânico e ambientalmente conscientes, com benefícios práticos ao bem-estar animal e à formação de engenheiros socialmente responsáveis.

Palavras chave: Dispositivo assistivo, Biomecânica, Projeto sustentável, Análise por elementos finitos, Mobilidade canina

1. INTRODUCTION

The increasing prevalence of hind limb paresis in medium-sized dogs necessitates the development of effective assistive devices to enhance their mobility and overall well-being (GILLETTE *et al.*, 2008). Traditional mobility aids

often fail to adequately address the biomechanical and comfort requirements of these animals, highlighting a significant gap in current veterinary assistive technology (WILLIAMS *et al.*, 2023).

Recent advancements in canine locomotor analysis have provided deeper insights into the biomechanics of canine movement, which are crucial for designing effective mobility solutions (ERAZO *et al.*, 2022). Studies have demonstrated that assistive devices must accommodate the natural gait patterns and joint movements of dogs to prevent secondary complications and ensure comfort (BEOKHAIMOOK *et al.*, 2020; MCKENZIE & CHEN, 2022).

Moreover, the selection of materials plays a pivotal role in the design of canine assistive devices (VILAR *et al.*, 2015). The integration of eco-friendly materials, such as biodegradable polymers and sustainable composites, has been explored to reduce environmental impact while maintaining structural integrity (MICH, 2014). These materials offer a balance between durability and sustainability, aligning with the growing emphasis on environmentally conscious engineering practices (MARCATO *et al.*, 2022).

Computer-Aided Engineering (CAE) tools, particularly Finite Element Analysis (FEA), have become indispensable in evaluating the structural performance of assistive devices (TUMULU; SARKAR, 2017). By simulating various loading conditions and material behaviors, CAE facilitates the optimization of design parameters, ensuring safety and efficacy prior to prototype fabrication (KOHAR *et al.*, 2021). This approach enhances the reliability of the devices and streamlines the development process (ALANEME *et al.*, 2022).

In this study, we present the development of a biomechanically compatible mobility solution for medium-sized dogs with hind limb paresis, utilizing eco-friendly materials and CAE-based structural analysis (SHAHAR; BANKS-SILLS, 2002). Our approach encompasses a comprehensive design methodology that integrates biomechanical principles, sustainable material selection, and advanced engineering analysis to create an effective and environmentally responsible assistive device. This study was developed during the undergraduate course "Design Methodology I" (PME3320) at the Polytechnic School of the University of São Paulo (EPUSP) in the first semester of 2024.

The course serves as an introductory yet foundational discipline in the field of mechanical engineering design (DIETER and SCHMIDT, 2013). It aims to immerse undergraduate students in the systematic processes of product development, emphasizing the transition from problem identification to conceptual design (ASIMOW, 1962). Throughout the semester, students are exposed to essential engineering design tools, such as morphological analysis, functional decomposition, decision matrices, technical specifications, and feasibility studies (LESKO, 2011).

The course is deeply rooted in problem-based learning (PBL), where multidisciplinary teams address real-world challenges through iterative design cycles (TAO *et al.*, 2025). A key pedagogical objective is to foster critical thinking and autonomy, encouraging students to balance technical rigor with creativity and user-centered design (KARTTUNEN *et al.*, 2025). The culmination of PME3320 is the development of a conceptual or basic product design, substantiated by engineering rationale, CAD modeling, material selection, and preliminary simulations, which often serves as the technical foundation for subsequent implementation and business planning phases addressed in the follow-up course "Design Methodology II" (PME3421).

2. METHODOLOGY

Following the completion of the feasibility analysis, a set of viable conceptual solutions was generated to address the challenge of restoring mobility in medium-sized dogs affected by hind limb paresis due to aging-related degeneration (SHEN *et al.*, 2024). This stage involved the definition of functional, operational, and constructive requirements, along with the identification of constraints and design criteria, to formally establish the technical specifications of the product to be developed (FUCHS *et al.*, 2014; GOLDNER *et al.*, 2015).

Subsequently, four alternative solutions were devised and submitted to a preliminary assessment considering physical feasibility, economic viability, and financial practicality (MOYO & MUSHIRI, 2025). The shortlisted concepts were as follows:

- Solution 1: A flexible bar made of elastic material, integrated into a harness that conforms to the dog's spine, extending down to the ground where it terminates in a wheel. This structure supports the hindquarters while allowing locomotion via the forelimbs. The bar must combine adequate flexibility to accommodate changes in posture with sufficient mechanical strength to resist applied load.
- Solution 2: A design inspired by conventional wheelchairs, modified with a tri-wheel configuration on each side to enhance traversal over uneven terrain and staircases. This configuration increases ground contact area and dynamic stability.
- Solution 3: A sustainability-oriented reinterpretation of the traditional wheelchair, constructed from recycled materials. This approach prioritizes resilience, affordability, environmental responsibility, and marketability.
- Solution 4: A hybrid design combining the features of a wearable harness and a detachable wheelchair module. The harness provides daily support, while the modular attachment offers full mobility assistance when needed, thereby improving usability and owner convenience.

Preliminary visual representations of these alternatives were generated using the DALL·E image synthesis tool and are shown in Fig. 1.

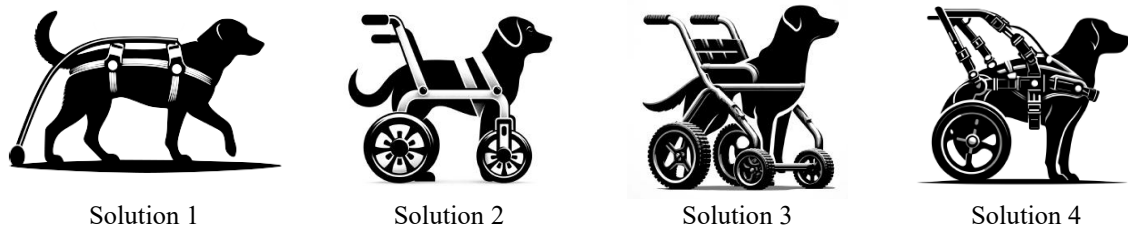


Figure 1. Draft of emerged solutions

The subsequent phase of the project, the basic design stage, was aimed at selecting the most promising alternative and defining its structure in detail. Each concept was evaluated according to the previously established design criteria, with a focus on identifying technical strengths and limitations. The selected solution was then subjected to in-depth modeling, structural analyses, and parameter sensitivity studies to determine the functional range of critical variables, assess the behavior of key components, and understand the influence of internal and external factors on product performance (GILL *et al.*, 2020).

The evaluation process began with a comparative analysis of the most promising alternatives, introducing an inherent level of subjectivity and uncertainty, particularly in the attribution of importance to specific criteria. To mitigate these factors, a structured, quantitative approach was adopted by employing a weighted decision matrix (MURENA *et al.*, 2019). In this framework, evaluation criteria were arranged in rows, while the alternative solutions were presented in columns. Each criterion was assigned a relative weight reflecting its importance to the project, and each alternative received a performance score against each criterion (MUSTAFA *et al.*, 2015).

The evaluation criteria were selected to comprehensively address the most relevant technical and user-centered aspects of the design problem (OLABANJI & MPOFU, 2019). The selected criteria are:

- Canine Comfort (C1): Assesses the ergonomic and physiological comfort afforded by the solution to the animal. Designs that minimize physical stress and allow natural posture and motion are rated higher.
- Ease of Use for the Owner (C2): Evaluates the operational simplicity of attaching, removing, and operating the device. Solutions requiring minimal physical effort and intuitive interaction are preferred.
- Durability (C3): Measures the structural robustness and long-term reliability of the design. High scores are assigned to solutions employing wear-resistant materials and sturdy construction.
- Cost (C4): Assesses the economic feasibility of the design, including material cost, manufacturability, and scalability. Affordable, high-value alternatives receive higher scores.
- Sustainability (C5): Evaluates the ecological footprint of the solution. Recyclable or biodegradable materials and low-emission processes are favored.
- Flexibility (C6): Assesses adaptability to various usage contexts, including indoor/outdoor environments, different terrains, and animal sizes.
- Aesthetics (C7): Considers the visual appeal and design integration with the lifestyle expectations of pet owners.

To assign the weights of each criterion, a binary pairwise comparison matrix was constructed. Each criterion was compared against the others, and a binary weight (1 or 0) was attributed depending on whether it was considered more or less important in the pairwise comparison. The final weights were computed as the ratio of times each criterion was prioritized over the total number of comparisons. This method constitutes a simplified implementation of the Analytic Hierarchy Process (AHP), which typically uses graded comparison scales (MOSLEM *et al.*, 2025). The resulting weights are summarized in Tab. 1.

Table 1. Criterion weights

	C1	C2	C3	C4	C5	C6	C7	Weight
C1	1	1	1	1	1	1	1	7/28
C2	0	1	1	1	1	1	1	6/28
C3	0	0	1	0	1	0	1	3/28
C4	0	0	1	1	1	0	1	4/28
C5	0	0	0	0	1	0	0	1/28
C6	0	0	1	1	1	1	1	5/28
C7	0	0	0	0	1	0	1	2/28

Arbitrary scores are assumed to be assigned to the solutions in each criterion, using a scale ranging from 0 to 10. The sum of the scores multiplied by the respective weights in all criteria will result in the total scores, allowing the determination of the best solution. This process results in the decision matrix presented in Tab. 2.

Table 2. Decision matrix

	Weights (W)	Solution 1		Solution 2		Solution 3		Solution 4	
		Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S
C1	7/28	7	49/28	6	42/28	7	49/28	8	56/28
C2	6/28	6	36/28	8	48/28	8	48/28	9	54/28
C3	3/28	7	21/28	7	21/28	6	18/28	6	18/28
C4	4/28	5	20/28	6	24/28	10	40/28	7	28/28
C5	1/28	4	4/28	5	5/28	10	10/28	5	5/28
C6	5/28	6	30/28	8	40/28	6	30/28	7	35/28
C7	2/28	5	10/28	7	14/28	7	14/28	7	14/28
Sum	28/28	x	170/28	x	194/28	x	209/28	x	210/28
End result		x	6,1	x	6,9	x	7,5	x	7,5

Solutions 3 and 4 achieved significantly higher scores compared to the other alternatives. Based on this quantitative outcome, combined with the design team's qualitative preference for these two options, Solution 4 was ultimately selected as the foundation for the development of the biomechanically-compatible mobility device for dogs.

3. RESULTS

The technical drawings presented in Figure 2 were developed using Fusion 360 and are based on standard anthropometric dimensions of medium-sized dogs (RAJASRIVALLI *et al.*, 2023).

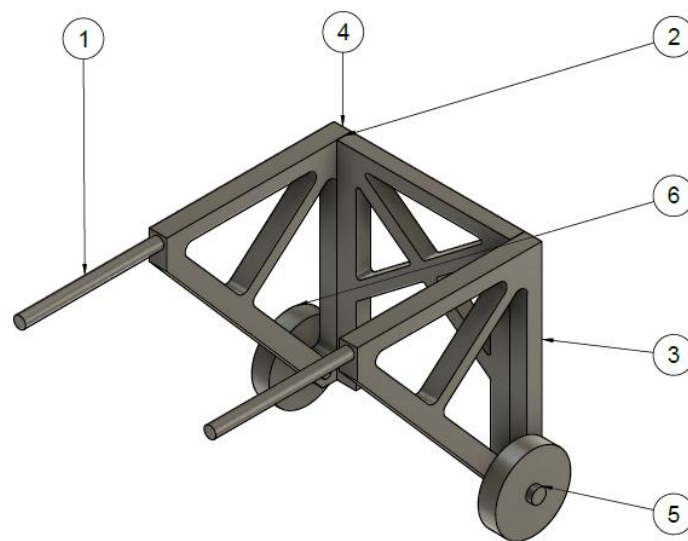


Figure 2. Isometric view of biomechanically-compatible mobility device for dogs

All structural components were meticulously dimensioned to ensure functionality, comfort, and safety, in accordance with the specifications defined during the feasibility study. The components are numbered accordingly: Side bar (1), Rear frame component (2), Right side frame (3), Left side frame (4), Locking pin (5) and Wheel (6). At this stage, the animal attachment interface, a flexible, textile-based element, was intentionally excluded from CAD modeling due to its adaptable nature and low structural relevance. In contrast, the rigid elements of the device were fully modeled to support precise dimensional analysis and manufacturability.

Critical interfaces, such as the wheel shafts and structural joints, were specified to accommodate commercially available components, facilitating both assembly and maintenance. The detailed drawings aim to provide a clear understanding of the device's physical architecture and to justify design decisions based on performance, usability, and durability. The technical drawings of the biomechanically-compatible mobility device for dogs are presented in Fig. 3.

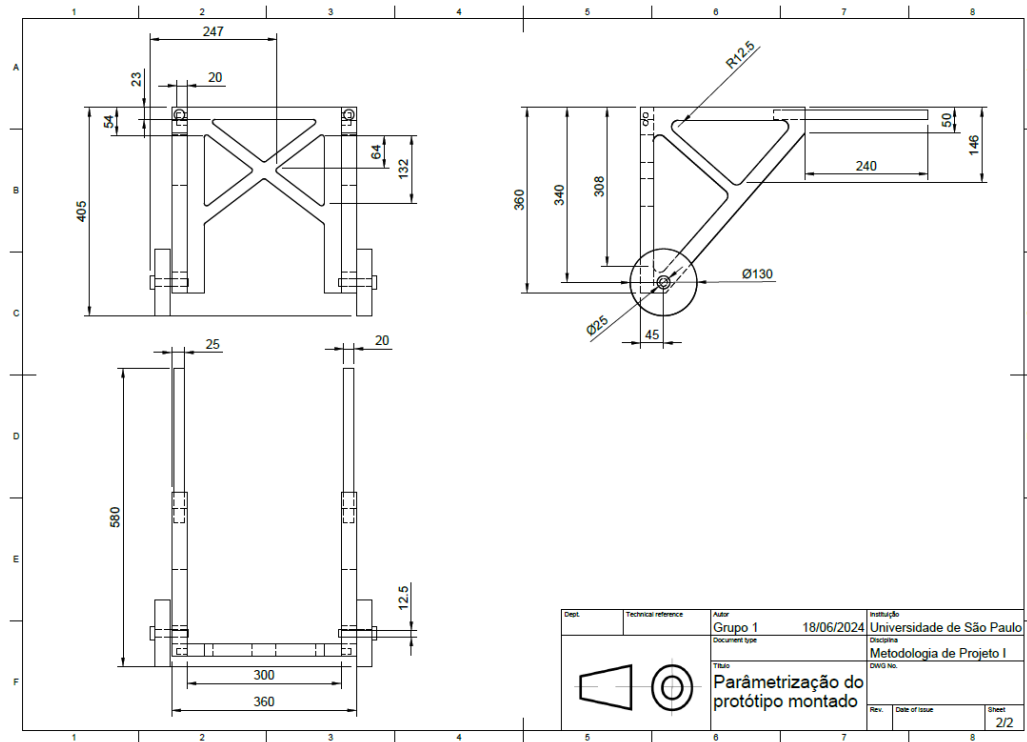


Figure 3. Mobility device technical drawings

To gain a preliminary understanding of the functional behavior of the proposed device, a sensitivity analysis was conducted to evaluate the influence of selected design parameters on overall system performance. The first parameter considered was the stiffness of the structural material used in the construction of the mobility aid.

This analysis was performed using finite element simulations based on a 3D CAD model developed by the team using Autodesk Fusion 360 (PATIL *et al.*, 2024). The simulation setup applied fixed boundary conditions at the wheel contact points, replicating a static equilibrium state in which the wheelchair is supported both by its wheels and by the mass of the animal. A downward force equivalent to the weight of a 15 kg dog, representative of a medium-sized breed, was applied vertically at the appropriate load-bearing interface.

The materials selected for comparison were corrugated cardboard, polyethylene terephthalate (PET), silicone, and bamboo. For each material, the following mechanical properties were specified in the software: density, Young's modulus, and Poisson's ratio. Material data for PET and silicone were sourced directly from Fusion 360's built-in material library. For cardboard, mechanical properties were obtained from Magalhães *et al.* (2006), while the properties of bamboo were referenced from Ghavami & Marinho (2005). Simulation results revealed notable differences in material behavior under loading as presented in Fig. 4.

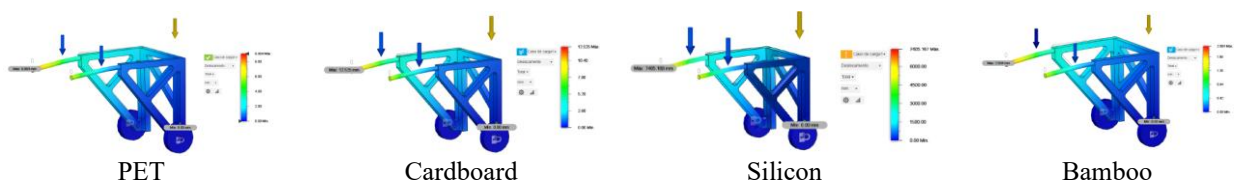


Figure 4. Finite Element Analysis to compare possible materials

Bamboo exhibited the least displacement, indicating the highest stiffness among the materials tested, while silicone displayed excessive deformation, far exceeding acceptable limits, rendering it structurally inadequate for the intended application. In contrast, PET and cardboard demonstrated similar performance, both exhibiting moderate and mechanically acceptable levels of displacement under the applied load. Despite bamboo's superior stiffness, the combination of structural adequacy, ease of handling, and widespread availability led to the selection of corrugated cardboard as the preferred material for subsequent design iterations and analysis.

The dimensional configuration of the proposed mobility device was defined to meet the functional requirements identified during the feasibility study, particularly for medium-sized dogs. The device was designed to allow for smooth locomotion over uneven terrain, including grass and small steps, while ensuring natural posture and comfort. Key

reference dimensions were established based on standard canine anthropometry (BURBIDGE; PFEIFFER, 1998): Length (560 mm), Width (360 mm) and Height (405 mm).

These dimensions aim to support biomechanical compatibility, maintain natural movement, and minimize any postural deviation from the animal's preexisting gait. Despite being dimensioned for an average-sized dog, the structure provides sufficient tolerance to accommodate a broad range of sizes due to the flexible nature of the harness interface.

Mass constraints were also considered: the total weight of the wheelchair was limited to 4.5 kg, ensuring ease of transport and minimizing physical burden on the animal. This threshold aligns with biomechanical load limits established for medium-sized dogs (WALTER & CARRIER, 2011), considering weight distribution and the animal's center of gravity (VOSS *et al.*, 2010).

The CAD model was developed with detailed front and side views to verify spatial compatibility and structural symmetry. Critical elements such as wheel alignment and rear limb supports were validated to prevent asymmetric loading, which could impair comfort or stability. A 3D model of a medium-sized dog was also inserted into the virtual wheelchair to assess the spatial interaction and confirm proper fit, range of motion, and postural alignment.

Material selection played a central role in achieving a lightweight, structurally sound, and sustainable design. A comparative analysis was conducted among bamboo, PET, PVC, aluminum, and corrugated cardboard. Criteria included structural resistance, availability, cost, and environmental impact.

Based on finite element results, cardboard emerged as a technically viable option, demonstrating sufficient strength to support the animal's weight while maintaining low density, which directly contributes to mobility and user comfort. In addition to mechanical performance, cardboard was favored for its affordability and ease of procurement, with economic studies supporting its use as a viable substitute for conventional materials without compromising quality (DE SOUZA *et al.*, 2016). Its adaptability to various manufacturing dimensions further enhances process efficiency and reduces tooling requirements.

Environmentally, cardboard offers significant advantages. It is biodegradable and widely recyclable, presenting a minimal ecological footprint throughout its lifecycle (TURRINI, 2017). This positions it as a preferable alternative to materials such as PVC, which present well-documented sustainability concerns due to harmful production processes and limited recyclability.

To mitigate concerns regarding moisture sensitivity, a coating strategy was developed. The application of resin-based sealants proved effective in enhancing durability by creating a hydrophobic barrier against moisture, dust, and abrasion, while preserving adhesion and flexibility (ALSABEK *et al.*, 2021). Additional protection was explored through waterproof varnishes, which further improved long-term water resistance and structural integrity (CHOPRA *et al.*, 2021).

By selecting corrugated cardboard and adopting protective coatings, the project not only achieved its functional and economic goals but also aligned with contemporary principles of sustainable engineering and environmentally responsible product development (MARINELLI *et al.*, 2021).

A critical aspect of the design process involved verifying that the system and its components are not intrinsically unstable, identifying instability zones within the design parameter space to avoid them, and assessing potential risks and consequences associated with disturbances that could compromise system functionality. The device is expected to operate over uneven surfaces, including grassy terrain up to 10 cm in height, as defined in the functional specifications, and to ascend and descend standard curbs approximately 15 cm high, consistent with urban accessibility standards (MACHADO; OLIVEIRA, 2021). These conditions test the resilience of the suspension system, particularly the damping and spring elements.

To ensure curb traversal, the design specifies the use of wheels with a minimum diameter of 12 inches (≈ 305 mm), such that the curb height remains below half the wheel radius, thus preserving forward momentum and minimizing the torque required to overcome the obstacle. To evaluate the response of the wheelchair to vertical perturbations, such as descending from a 15 cm drop (the most critical scenario), a single degree-of-freedom vibration model was used. This model follows the classical formulation for vertical motion under impact loading as presented by Vierck (1979). The vertical excitation force was assumed to act along the same axis as the suspension compression and was applied at the wheel hub, minimizing any influence on rotational dynamics.

Given that the canine user retains full function of its forelimbs but lacks posterior support, it was assumed that the rear suspension system must absorb approximately half of the combined weight of the dog and the wheelchair. For analytical simplicity, the analysis was further reduced to a single wheel, bearing one-quarter of the total system weight.

This model enabled the evaluation of displacement, natural frequency, and damping behavior under vertical excitation, validating that the suspension design offers sufficient dynamic compliance without compromising stability or comfort. A schematic of the modeled suspension system is provided in Fig. 5.

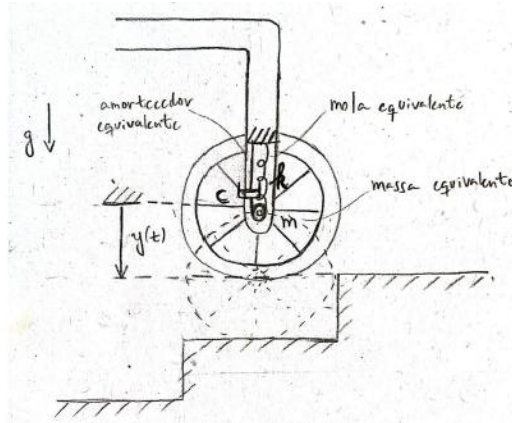


Figure 5. Conceptual diagram of the suspension system under maximum vertical loading condition

To evaluate the vertical dynamic response of the device, a single degree-of-freedom damped vibration model was adopted. This model represents the suspension system subjected to free vibration after a vertical perturbation, specifically, a drop of 15 cm, simulating the descent from a standard urban curb. The governing equation for a damped system is presented in Eq. (1):

$$m \ddot{y}(t) + c \dot{y}(t) + k y(t) = 0 \quad (1)$$

Where m is the equivalent mass, C is the equivalent damping coefficient, k is the spring stiffness, $y(t)$ is the vertical displacement over time. The system's response depends on the damping ratio ζ , defined by Eq. (2):

$$\zeta = \frac{c}{c_c} \quad (2)$$

Given that $\zeta < 1$, the system exhibits underdamped behavior, typical of mechanical suspension systems using springs and dampers. This results in oscillatory motion with an exponentially decaying amplitude. The decay time τ_d is the time required for the amplitude to reduce to 1/e of its initial value is given by Eq. (3), where $\omega_n = \sqrt{\frac{k}{m}}$ is the natural frequency of the system:

$$\tau_d = \frac{1}{\zeta \omega_n} \quad (3)$$

For the analysis of the suspension system, it was decided to consider the dog's mass as 20 kg, with a purpose analogous to the application of a safety coefficient in the dimensioning. Using previously defined design constraints, dog mass (20 kg) and wheelchair mass (4.5 kg), the equivalent mass per wheel is given by Eq. (4):

$$m = \frac{1}{4} (m_{dog} + m_{wheel\ chair}) = \frac{1}{4} (20 + 4.5) = 6.125 \text{ kg} \quad (4)$$

The working travel of the suspension was defined as 5 mm, a conservative value derived from simplified kart suspensions. The equivalent spring constant was estimated using Eq. (5):

$$k = \frac{m g}{0.4 - 0.6 W T} \approx 150 \frac{N}{m} \quad (5)$$

The critical damping coefficient was calculated using Eq. (6):

$$C_c = 2 \sqrt{k m} \approx 61 \text{ Nsm}^{-1} \quad (6)$$

A damping ratio of $\zeta=0.3$ was selected, within the recommended range (0.2 to 0.4) for underdamped mechanical systems (LEI *et al.*, 2017). Hence, the equivalent damping coefficient becomes as per Eq. (7):

$$C = \zeta C_c \approx 18 \text{ Nsm}^{-1} \quad (7)$$

Neoprene tires were specified for the wheels, due to their intrinsic damping characteristics, which supplement the mechanical suspension response (AUTOTRAVI, 2022). These are commonly used in karts lacking sophisticated

suspension systems. Thus, the calculated decay time is approximately $\tau_d = 0.68 \text{ s}$ indicating that the system stabilizes and returns to equilibrium in less than one second after a maximum perturbation of 5 mm. These values confirm that the designed suspension system can effectively attenuate vertical oscillations and restore stability promptly after localized impacts, ensuring comfort and safety for canine use.

To ensure safe and comfortable operation, a wheelchair must maintain stability on inclined surfaces commonly encountered in outdoor environments. For canine users, tipping over can lead to significant distress and an inability to self-correct without external assistance. Therefore, the device must tolerate a reasonable slope angle (α) without compromising its balance. A simplified analytical model was employed to assess tipping conditions (Fig. 6 a). The system was modeled as a point mass (m) suspended at a height (h) from the ground, supported by two-wheel contact points separated by a distance (d), and positioned on a plane inclined at an angle α relative to the horizontal. Lateral wheel slippage was neglected to isolate the effect of gravitational torque on stability.

By analyzing the equilibrium condition, the critical tipping angle was determined as a function of the mass height and wheelbase. The inequality governing tipping can be derived from static torque balance, comparing the destabilizing moment due to gravity with the stabilizing moment from the base support.

To visualize the sensitivity of the system to changes in geometry and load distribution, the model was implemented in the Desmos interactive simulation environment (Fig. 6 b), allowing real-time manipulation of parameters (m , h , d , α) and graphical observation of their effects on stability thresholds, calculated by Eq. (8) and Eq. (9).

$$N_1 = m g \left(\frac{\cos \alpha}{2} + \frac{h}{d} \sin \alpha \right) \quad (8)$$

$$N_2 = m g \left(\frac{\cos \alpha}{2} - \frac{h}{d} \sin \alpha \right) \quad (9)$$

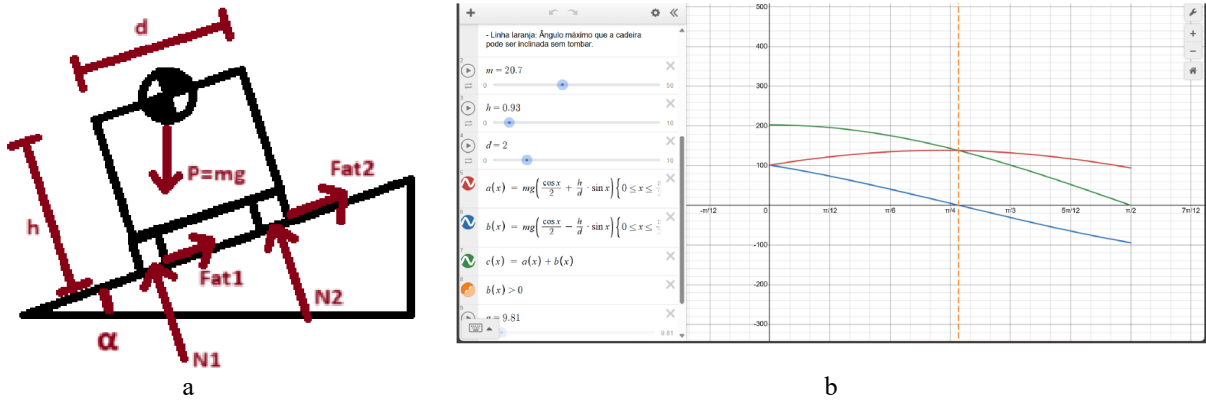


Figure 6. a) Diagram of the variables considered in the calculation; b) Normal force as a function of inclination

A stability bound was obtained from the tipping-condition equation and its parametric evaluation in Desmos. The maximum slope angle that prevents overturning is approximately 24° for the adopted geometry and assumptions: no lateral slip, quasi-static balance about the downhill contact, and center of mass height and wheelbase as specified. This value should be treated as a design limit; operational use is recommended with an adequate safety margin below this threshold.

4. CONCLUSIONS

This study presented the conceptual design and preliminary validation of a biomechanically-compatible mobility aid tailored for medium-sized dogs affected by hind limb paresis. The project was developed as part of an undergraduate engineering design course and followed a structured methodology that incorporated problem definition, alternative generation, feasibility evaluation, material selection, and basic structural analysis.

Among the four proposed solutions, the selected concept prioritized sustainability, affordability, and user-centered design. Through comparative analysis using a weighted decision matrix, a wheelchair constructed from corrugated cardboard was chosen as the optimal solution, striking a balance between structural performance, environmental responsibility, and manufacturing simplicity.

Finite element simulations confirmed that cardboard offered sufficient stiffness to support the weight of a medium-sized dog, while remaining lightweight enough to avoid impairing locomotion. Protective coatings such as resins and waterproof varnishes were explored and proposed to extend material durability under real-world conditions. Dimensional compatibility was ensured through CAD modeling and anthropometric referencing, with further validation via digital simulations involving a canine model.

Beyond the technical contributions, this project also serves as an educational case study in applied engineering design. It demonstrates how sustainability, biomechanics, and affordability can be successfully integrated into the early stages of product development, even within the constraints of a university-level course. The results indicate that such assistive devices can be designed with a high level of functionality, while promoting ethical and environmentally conscious engineering practices.

Future work may involve physical prototyping, in vivo testing with veterinary supervision, and refinements to improve ergonomic integration and long-term durability.

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7. RESPONSIBILITY FOR THE INFORMATION

The authors bear full responsibility for the accuracy and integrity of the information presented in this work.