Development and Kinematic Study of a Spring-Integrated Two-Link Prosthetic for Canine (Indian Pariah) Limb Support

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Abstract
Lower limb amputation in dogs is often a result of trauma, tumors, or congenital deformities which affects mobility and quality of life. Current prosthetic solutions are generally limited in their adaptability and seldom account for the biomechanics of partially amputated limbs. This study details the design and validation of a spring-integrated, two-link prosthetic limb that returns limb length while incorporating some dynamic energy storage and release component to replicate function similar to natural tendon/ligament systems. The results begin with modeling of CAD and the construction of prototypes using light PVC rods and 3D printed component parts made of PLA for rigid elements, TPU for flexible/ compliant contact surfaces, and stainless-steel tension springs for energy return. Bench validation including both static and dynamic loading demonstrated notable similarity between calculated results and bench validation findings. Initial and sustained loads were very similar for the forelimb 177N and compression of the spring was 24.7mm, close to the predicted 25mm, which means the prosthesis was storing 2.2 J of elastic energy per stride. The purpose of prosthesis design and prototypes was to utilize low-cost, available materials, while maintaining structural safety with stresses below the material yield limits. This work demonstrates that affordable, biomechanically informed prostheses can be developed for canine patients, addressing the limitations of socket-based devices. By integrating dynamic spring assistance with scalable fabrication methods, this approach provides a clinically relevant pathway to improving rehabilitation and quality of life for amputee dogs.

Introduction

In dogs, lower-limb amputation usually occurs as a consequence of trauma, neoplasia, congenital deformities, or other pathological reasons, resulting in some form of reduced mobility [16]. Progressive sophistication in veterinary orthopedic care, prosthetics in animals, and the goal of restoring full function and quality life is present, but current commercial devices are limited, especially for those who are partially amputated and have an upper portion of the limb remaining. All known devices designed for lower-limb amputation of dogs are designed with a specific model for limb loss and have little to no direct adaptability to the biomechanical aspects or anatomical changes of a partially amputated limb [13].

A functional-amplifying prosthetic must do more than return the limb length in a static position; it must be able to reintegrate the dynamic functions of the natural joint to provide a more smooth, energy-efficient gait cycle. Conventional devices often fail to accommodate the biomechanical complexity of partially amputated limbs, leading to insufficient stability, high complication rates, and poor long-term satisfaction among patients and owners. Current prosthetic options include socket-based exoprostheses, 3D-printed custom devices, and surgically anchored systems such as intraosseous transcutaneous amputation prostheses (ITAP). While these approaches have improved patient outcomes in some cases, they are often associated with complications like skin irritation, suspension difficulties, and high costs, especially when advanced or custom-made designs are employed [4]. One main limitation of current designs is their inability to store and release energy as would occur when utilizing biological elements of tendons and ligaments during normal locomotion—something that is not currently addressed with average stabilization of joint-limbs in conventional prosthetic limbs [15]. Passive mechanical elements such as tension springs are a valuable avenue to pursue in order to resemble the store-and-release function and provide an opportunity to reduce compensatory stress in the rest of the musculoskeletal system and maintain adolescent gait stability in future adult dogs [17].

The design entails designing and fabricating a spring-integrated, two-link prosthetic limb for dogs with a partial lower-limb amputation. The spring-integrated prosthesis includes two interconnected articulating links: the proximal link connects with the residual limb and the distal link connects with the terrestrial environment. A pin joint connects both links together, with a pair of tension springs housed at both the proximal and distal joints. The tension springs are designed to store energy during limb loading, and release energy during limb unloading, ultimately assisting in creating a limb level that is more dynamically stable as the pet walks.

From an economic perspective, this project proposes a cost-effective solution to Indian and international prosthetics that can range from approximately ₹9,500–₹38,000 locally, and around $1,500–$2,000 (~₹125,000–₹170,000) abroad [1]. Given our use of affordable materials and rapid prototyping, we expect initial prototype production (as opposed to design) to be in the range of ₹10,000–₹20,000 per unit, in range of the cost of commercial devices.

Despite technological advances, there is still very little use of biomechanical simulations, consistent kinematic testing, or evidence-based design in the veterinary prosthetics field [14]. There is an increasing need for collaborative, scientific, interdisciplinary approaches to prosthesis development, including more traditional engineering methodologies and veterinary biomechanics principles. This study intends to build on previous research and contribute to prosthetic limb design for canine rehabilitation that could ultimately result in greater efficacy in clinical practice. By targeting a largely unmet clinical need, this innovation stands to set new standards in veterinary prosthetics, offering a scalable and accessible solution for partial amputees in India and beyond. The integration of biomechanical principles and evidence-based engineering has the potential to transform the canine prosthetic market, increase adoption rates, and significantly enhance the quality of life for affected dogs and their owners.

Literature review

Mendaza-DeCal, et al. [2] sought to mitigate the economic and knowledge issues in veterinary orthotics and prosthetics by simplifying the manufacture of devices with 3D scanning and fused deposition modeling (FDM). The researchers developed a scaling equation to allow them to change sizes of the devices without having to remanufacture them. The research team developed three new assessment scales to assess adaptation of orthoses and prostheses on animal subjects. The research team modified the method to assess adaptation based upon the veterinary form of the plan. A total of 10 animals [nine dogs; one calf] were involved in the study based upon need for either/and/or socket prostheses or orthoses. The vet team obtained a 3D complete limb area, using a hand-held 3D scanner, to scan the orthotic/prosthetic areas. The 3D area was produced to STL files to allow for scaling areas with the scaling equation. The scaled design would be completed with SolidWorks based off of the 3D area. Once the designs were made, the devices were FDM manufactured with the use of PETG and thermoplastic polyurethane (TPU) to complete the orthotic/prosthetic device. There were two types of devices that were tested: the orthoses and socket depending on the dog's size. A clinical fitting was completed for the animal subjects and monitored for continued use at home. Six socket prostheses devices and five orthoses devices were manufactured for the potential animal subjects. The orthoses performed better for patient adaptation and tolerance by the canine patients, with most of the patients continuing to wear the device at home. The calf adapted well to restore bone structure on prostheses. Conversely, all dogs had limited success with the socket prostheses due to discomfort or stability control. The statistical analysis determined the scaling equation was valid and there were significant differences for the types of devices. The gaps identified in this study was the need for clinical outcome data, none of the participants were analyzed for cost outside of the US, and limiting of prosthesis, specifically in regards to 3D printing materials. Also, there needs to be biomechanical analysis and rehabilitation protocols for animal patients, specifically for canine based amputees wearing prostheses.

It was Figueroa-Peña's intent to create a methodology for the design of a dog forelimb prosthesis prototype that used anthropometric data, analytical calculations, and finite element analysis simulations [3]. The prosthesis model was designed for a dog, with a mass of 30 - 40 kg, the leg length (from elbow to forefoot) was 35 - 45 cm long, and was amputated at the elbow. Figueroa-Peña produced initial sketches for the design, which then developed SolidWorks designs and models focusing on the components subjected to the highest load. The mechanical characteristics were assessed using analytical calculations including the stress applied to a 25.40 mm diameter connection tube supporting 45 kg of load for a moment. Important design features were effectively tested and measured using simulations in SolidWorks and finite element analysis to measure the stress distribution and the deformation of the contact surface in order to confirm the ideal behavior of the dog forelimb prosthesis structure. The experiments validated the design qualities as the structure could support the probable loads expected to be applied to the design. The loads on the connection tube in relation to stress was calculated to achieve 882.9 kPa of stress under a nominal TL load of 441.45 N. The simulations did have maximum stress value from a low of 100.299 Pa to a high of 29,760 kPa with maximum deformation of 0.9708 mm. E-glass fiber was determined to be the best performing anisotropic materials out of the leg materials considered. ABS exhibited the most deformation simulation results. This process yielded a prototype that was successful due to its full compliance with the pure geometric and mechanical design parameters while maintaining a safe factor greater than 1.0. At this point, the prototype has not been built which is a significant gap. The second stage of this discussion would be to build a dog forelimb prosthesis prototype using the materials indicated and then further optimize the design of the prosthesis for improved performance and flexibility.

Wendland, et al. [4] sought to prospectively examine mid-term clinical outcomes of partial limb amputation with socket prostheses (PLASP) in dogs and to define a clinical protocol. There were twelve client-owned dogs that weighed over 10 kg with distal limb pathology that underwent partial amputation with at least 50% of the radius or tibia remaining. The dogs were fitted for prostheses post-operatively and follow up included gait analysis, radiographic assessment, and an owner satisfaction questionnaire. Eleven of the twelve dogs returned to quadrupedal gait, and their mean weight bearing distribution was 26% for thoracic limb prostheses and 16% for pelvic limb prostheses. The authors acknowledged that the functional outcomes were positive, however, 10 of the 12 dogs had complications of varying severities; examples included suspension issues with the prosthesis, pressure sores, bursitis, and infection. Of those 10 owners, 2 opted to discontinue use attributing use to the complications. Radiographic evaluation of the remaining dogs demonstrated mild remodeling, osteopenia, and sometimes bursal formation. Owner satisfaction was generally high, but could be reasonably perceived to be subjective. In this study, the authors noted several limitations: first and foremost the complication incidences were greater than expected when compared to retrospective data; second, the surgical technique lacks standardization that takes into account the unique canine anatomy; third, there was difficulty in suspending the prosthetic in the case of proximal amputations; there was also a lack of explanatory regarding how the limb was being carried, and lastly, the limited sample size evaluation breadth, and variability strongly limited generalizability. The authors concluded that PLASP has the potential to restore functional gait, though they note the need for improved surgical protocol, improved fitting of the prosthesis, and larger controlled studies.

Rincón-Quintero, et al. [5] focused on the development of a functional and low-cost prosthesis for partially amputated forelimbs in canines and sought to improve the mobility of those animals, reduce secondary pathologies, and enhance quality of life. The prototype dog they selected was a medium-sized Creole dog, with an amputation in the left forelimb. The authors reference Karl Ulrich's six-phase product development process in their development. Phase 1 of product development discussed the literature reviews they completed on prosthetic designs and materials. The authors utilized a selection matrix to evaluate all design iterations; Design 1 was selected for its articulation, sufficient spacing for the electronic system, and functional structural support. The prosthesis contains eleven 3D-printed components made from PLA that were flexible, strong, and environmentally friendly; and an orthopedic gratuitous neoprene stocking for the forelimb for its flexibility. An electronic system was developed to measure, collect, and allow for real-time monitoring of weight distribution through the use of a load cell, Arduino Nano computer, and HX711 microchip. The examples used LEDs and a buzzer to alert the dogs' handler if their weight was balanced correctly. The creators produced a fully functional prototype to incorporate cushioning and electronic systems. Although the device has potential, considering comfort, functionality, and sustainability, some inferred study limitations included the absence of a long-term durability test, limited clinical trials, or public trials for form and fit check if the dog moved itself, as well as a larger assessment regarding cost-effectiveness and biomechanical performance.

Rosen, S., et al. [6] assessed complications and outcomes after providing custom orthoses and prostheses to 43 canine patients over a 12-month period. Dogs were classified by type of device as carpal orthosis (CO), stifle orthosis (SO), tarsal orthosis (TO), and prosthetic device (PD). Data was collected via owner surveys, Client-Specific Outcome Measures (CSOM), and gait analysis (OGA) with a pressure-sensitive walkway. Statistical assessments included Fisher's Exact, Kruskal-Wallis, Spearman correlation, and ANOVA. Complications were common as 91% of patients had at least one complication and all dogs who used a PD had at least one complication. Skin complications were most common; especially in the first 3 months of use, and reported incidence for CO users was as high as 90%. Mechanical issues including loose screws and device parts were reported, and there were 7 dogs that demonstrated non-acceptance of the device and this was highest in PD users (55%). Gait analysis demonstrated % body weight (BW) improvement pre- and post-orthotic wear in CO and SO users; but did not improve in TO users. CSOM scores indicated clinical improvement for all devices when comparing baseline to final scores. However, study limitations included small sample sizes, absence of control groups, subjective data, inconsistent follow-up, and variability amongst patients' use of devices. While the study indicates a potential for clinical benefit, the authors concluded there is a need for greater objective research to assess long-term effectiveness.

Arauz, et al. [7] sought to provide veterinarians with evidence-based information about canine limb prostheses by reviewing recent surgical techniques, design and fabrication methods, and biomechanical studies. The authors classified prostheses as exo- and endo-exo prototypes, and included an extensive list of technologies such as CAD, 3D scanning, CT, MRI, and additive manufacturing. The biomechanical studies included motion tracking to evaluate the function of the musculoskeletal system while fitting and using the prosthesis. One conclusion was that modern advancements, including osseointegration and 3D printing, improved stability, fit, and comfort for the patient, while decreasing costs and fabrication time. Prostheses made on 3D CAD designs and potentially fit using the same tools demonstrated actual relative functionality to a normal limb. Retrospective studies reported 80% of owners reporting good to excellent quality of life following treatment, highlighting human-animal relationships; however, there remained many gaps. While a few studies included scientific evidence, many lacked scientific rigor and were often specific to a case. There was little to no primary literature on the effects of shock-absorbing pylons, suction socket fit protocols, and suspension systems. The use of endo-exo prosthesis was rare outside of veterinary constructs and kinematic protocols for evaluating amputation and prosthesis remained un-standardized. There were commercially available prostheses with limited geometrical applications for adaptability, and there were no studies on owner satisfaction, risk of prosthesis failure, or muscle-prosthesis integration.

Stupina et al. [8] attempted to evaluate the risk of knee osteoarthritis (OA) following tibial prosthetics to dogs using a one-stage osseointegration method, external fixation and controlled compression loading. Eight mongrel dogs underwent tibial osteotomy and unconstrained implantation of a Ti6Al4V alloy prosthesis combined with Ilizarov components. Three dogs in the experiment group were implanted, while five additional dogs were used as controls. Six weeks of compression and four months of duty cycle or loaded usage of the prosthesis was undertaken prior to euthanasia at six months for processing samples for histomorphometry. The nine was the first to provide weight bearing and some ability of movement with a limb, and one dog was fully weight bearing without lameness by the four month period. The histological findings, while supportive of the maintenance of overall cartilage architecture, indicated that significant changes had occurred. The thickness of calcified cartilage decreased with osteotomy prosthetics from pan cartilage and on each limb to two fold when compared to normal knees. The basophilic line of demarcation between uncalcified and calcified cartilage was lost. The subchondral bone volume and probable shape were affected negatively with a 1.9 fold decrease in density of opaque thickness, and volumetric trabecular bone density decreased from 46.94 % in the 5 control dogs to 22.31 % in three experimental dogs. Bone trabeculae appeared rarefied and poorly arranged. Cartilage and subchondral bone associations number were suggestive of increased risk of OA with tibial prosthesis implantation in dogs and the data accounted for only the intact knee joint and not for other possible pathology. Although small numbers, the study provided preliminary evidence warranting future investigations concerning long-term joint health following prosthetic usage in dogs.

Chris W. Frye sought to provide an overview of prosthetics in veterinary medicine, particularly as it pertains to amputations in dogs. [9] This paper looked at the increasing demand for prosthetics in veterinary medicine, the lack of scientific literature regarding its efficacy, and prosthetics could diminish gait and improve function in amputees. Frye employed a literature review and personal clinical experience to discuss the fitting and rehabilitation of prosthetics, selection for candidates for fitting, and how prosthetics are introduced into the amputation patient. Some of the notable discussion points included the biomechanical changes after amputation; the altered weight-bearing, and motion in joints when transitioning from an intact limb to an amputated limb particularly when it came to the carpus and hock joints of forelimb amputees and hindlimb amputees, respectively. The author articulated the importance of appropriate anatomy, adequate molding, appropriate fit and training of physical therapy post-prosthetic fitting. He discussed the importance of owner buy-in and owner education about the prosthetic. Two retrospective studies were discussed in the overall review; one of the retrospective studies returned 9 of the 12 had complications of the prosthetic usage while the majority was considered minor skin abrasions; the second retrospective study had short term complication rate of 62% with a long term complication of 19%. Regardless of complications, there was high owner satisfaction. This review concluded veterinary prosthetic use could improve life and ambulation for patients, while there are significant limitations exist including a lack of standardization between protocols and a lack of scientific studies remaining to describe best practices for designing and implementing prosthetics.

Kastlunger conducted the research put forth in this article to accommodate a canine with a congenital limb deformity. His work suggestively offered a viable way to benefit the canine and also reflected limitations associated with existing commercial products. His intent was to fabricate a prosthetic that not only offered an affordable and durable alternative to surgery but also an improvement in mobility and gait stability. The suitable test subject was a one year old female german shepherd with congenital deformity of the distal right forelimb. This research project received approval by IACUC, therefore, all procedures related to the dog were ethically applicable. The prosthetic was fabricated using a variety of custom 3D-printed parts (PLA material), as well as commercially available parts such as an aluminum rod and foam padding. A cast of the dog's limb was 3D scanned and CAD modeling was used to create the prosthetic parts. A finite element analysis (FEA) was completed with Autodesk Fusion 360 and abaqus to assess the strength and stress of the structure. Positive results determined that the prosthetic was capable of withstanding the high impact forces of gait, maintained a secure and comfortable fit on the dog’s limb, and stabilizing gait to allow for a redistribution of weight like an advancing tetrapod stance. The fabrication was both reproducible and practical for similar project contexts. Ultimately, the provided recommendations should focus on completing further mechanical tests including fatigue, and impact tests to assess durability/ failure modes of the selected materials.

Wendland et al. (2023) focused on determining clinical outcomes, owner satisfaction, and prognostic factors associated with socket prostheses in dogs with partial limb loss [12]. The authors examined 137 cases from the client database of a single provider of prostheses and received 50 responses (37% response rate) with 47 used in analysis. Overall, owners reported a high (46/47) level of satisfaction, with 95.7% of owners stating that they would attempt prosthetic treatment again. The author's report of clinical outcomes was also favourable, with 42 dogs reaching acceptable to full function. Short-term complications were observed in 62% of cases and long-term complications noted in 19%, with skin sores being the most common complication. The authors completed statistical analysis that indicated a significant positive correlation between duration of wear for the prosthetic and clinical outcome and satisfaction of the owner ($p = .01$). While all of the defects confirmed via radiograph were distal to the mid-radius/ulna or tibia/fibula, the authors did not find a significant positive or negative correlation of level of defect to outcomes. The authors acknowledged that the limitations of this study were its retrospective design and reliance on unvalidated owner-reported survey data, owners' recall could result in bias, as well as the fact that the included sample was nonrandomized and could have inflated the level of satisfaction. Finally, with the small number of cases involving mid-limb defects, it became difficult to produce any meaningful conclusions regarding the level of the defect as a prognostic factor. The authors proposed that future prospective studies reporting objective clinical data would further the understanding of the use of socket prosthesis and fill the gaps identified in their study.

Methodology

The study of the design was carried out in four components:

1. Computer-Aided Design (CAD) and parametric modeling of the prosthesis assembly.
2. Iterative prototyping using a 3D printing process with both PLA and TPU material properties, which allow us to produce a customized device for the patient, and iteratively refine the final design.
3. Sensor-based physical testing, including the use of basic force and motion sensors, to record joint motion and verify the simulation data.

The study was conducted using a representative model of an Indian Pariah breed dog, selected for its average body weight of approximately 20 kg. The residual limb parameters were defined with an average bone diameter of 5 cm and bone length of 24 cm, which served as the baseline anatomical dimensions for prosthesis design. These measurements ensured that the prosthesis was dimensionally appropriate and mechanically comparable to the expected loading and support conditions.

Based on established canine biomechanics, a 60:40 mass distribution was used i.e., 60% of body weight is supported by forelimbs, 40% by hindlimbs. Hence, each forelimb bears approximately 6 kg (29.4% of total weight) and each hindlimb bears approximately 4 kg (19.6% of total weight). In a static stance, body weight is passively distributed, with the forelimbs supporting 60% and the hindlimbs 40% of the total mass. During running or trotting, peak limb forces increase above static values due to momentum and acceleration. Vertical ground reaction forces on a single hindlimb can reach approximately 1.5-3 times its static load. In sitting, most body weight shifts to the pelvis and hindlimbs, but with more area in contact and less vertical load per limb [7][11].

Therefore, the maximum static load for forelimbs = $6 \times 9.81 = 58.9N$
Maximum running load for forelimbs = $58.9 \times 3 = 177N$

And, the maximum static load for hindlimbs = $4 \times 9.81 = 39.2N$
Maximum running load for hindlimbs = $39.2 \times 3 = 117.7N$

Calculation for tension spring:

The material chosen is stainless steel as it has high tensile strength, excellent corrosion resistance, and biocompatibility. Stainless steel can withstand repetitive load cycles that come in animal prosthetics without deforming. Stainless steel excels in moist, outdoor, and biologically active environments critical for canine prosthetics, where exposure to water, soil, and body fluids is unavoidable. This property ensures long-term, maintenance-free operation. Stainless steel provides a reliable balance between high performance and affordability, making it well-suited to cost-sensitive veterinary applications where reliability and scale are important.

Deflection assumed for smooth gait = 25mm = x

Spring constant, k = $\frac{F}{x} = \frac{177}{25} = 7.08$

$$k = \frac{Gd^4}{8D^3n}$$

Where,
G = shear modulus ≅ 79,000 N/mm^2 for stainless steel
D = mean coil diameter;
d = wire diameter;
n = number of active coils.

Potential energy, U = $\frac{1}{2}kx^2$

Therefore, U = $\frac{1}{2}(7.08)(25)^2 = 2.2125$ J

D = Cd

Where C = spring index, which is the ratio of the mean coil diameter (D) to the wire diameter (d).

Therefore, C = $\frac{D}{d}$

Making, $k = \frac{Gd}{8C^3n} \Rightarrow d = \frac{k8C^3n}{G}$

Assuming, C = 8 (good for manufacturability);
n = 8 (good for balance rate vs height).

A typical range for the spring index is between 4 and 12. A smaller spring index (close to 4) indicates a relatively tight coil, which can produce higher stresses and may be more difficult to manufacture. A larger spring index (above 12) means the coil is looser, which can reduce stiffness but increase the risk of buckling or tangling during operation.

Substituting values for: $d = \frac{k8C^3n}{G} = \frac{231997.44}{79000} = 2.937mm$;
therefore , taking d = 3mm and D = 24mm.

For free length:

d = 3mm;
Active coils = 8
Inactive coils = 2 (assumed)
Total coils = 10
therefore, $solid\ height\ =\ total\ coils\ \times\ wire\ diameter\ =\ 30mm$
Clearance = 10mm
Deflection = 25mm
Therefore, minimum free length = 65mm

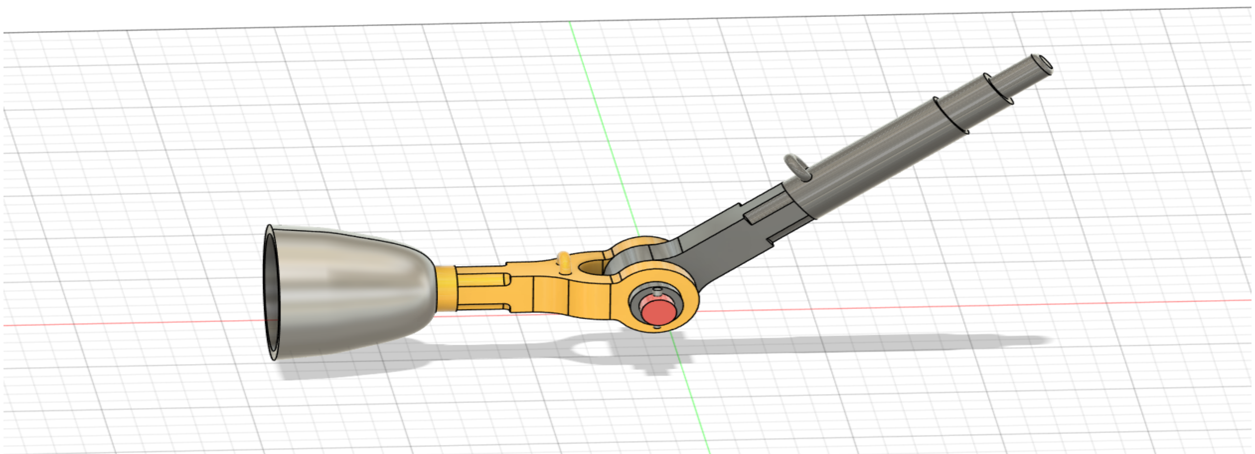

Fig 1. CAD prosthetic leg assembly for dog with attachment

Polyvinyl chloride (PVC) pipes were chosen for the structural rods due to their rigidity, lightweightness and the ability to customize. Also, they provided flexibility and rigidity balance and most importantly cost-friendly lightweight materials that can be further customized by shaping or cutting. The base component that has an interface with the rod chosen is thermoplastic polyurethane (TPU) which is flexible and can absorb impact on the ground. As shown in the picture below, the base component has a solid attachment using velcro straps for easy attachment and adjustment. The base was made using TPU (Thermoplastic Polyurethane) because of its ability to provide flexibility, to absorb shock and resist wear. By using TPU we believed that it would help to soften contact force to the ground with the base component and aid in limiting the impact stress to the residual limb to create comfort when ambulating.

The knee joint consists of a three-dimensional model of a knuckle joint made from the PLA material by 3D printing. Additive manufacturing was chosen to fabricate the knee joint because of the favored properties from 3D printing using PLA and the desired rigidity or desired rigidity with the ability to torque and not simply flex when attaching a prosthetic leg. PLA is also well suited for this scenario as a knee joint prosthetic component; this component is a hinge therefore the joint needed to seamlessly articulate and provide stable force transfer without bending in too much excessive flex. The paw was also 3D printed in TPU to provide necessary flexibility and cushioning during ground contact. Similar to the base, the paw is printed in TPU to provide flexibility and impact absorption on ground contact points, mimicking natural paw pad properties. The tension spring was attached at both ends to the PVC rods near the knuckle joint to provide resistance during compression and assist with energy return in limb movement.

Kinematic and kinetic data were obtained using a compact suite of instruments centered on inertial measurement and foot-mounted force sensing. An MPU-6050 module (3-axis accelerometer and gyroscope) was rigidly affixed next to the hinge on the lower link to obtain angular velocity, linear accelerations and derive joint angles using sensor fusion. The IMU ran at 100 Hz, and raw data was logged to a microSD card using an ESP32 microcontroller. Ground contact forces were measured using either a distributed FSR array embedded in the TPU paw pad (4 sensor elements to obtain fore/heel and medial/lateral loading), or a single in-line load cell in trials requiring increased accuracy. Spring compression was measured using a compact linear potentiometer fixed in parallel with the spring to provide spring force from displacement using the established spring rate (k).

Primary quantitative outcomes were selected to characterize both mechanical assistance and functional gait changes. Kinematic outcomes included maximum joint flexion and extension angles per stride, peak angular velocities, and time-normalized angular trajectories over the gait cycle. Kinetic outcomes were focused on vertical ground reaction force metrics, and loading rate. Spring dynamics were quantified by maximum compression (mm), peak spring force (N), and per-stride elastic energy stored and returned.

Fig. 2: Spring-integrated two-link canine prosthetic limb prototype.

Figure 2 demonstrates the complete prototype of the spring-integrated two-link canine prosthetic limb designed as part of the study. The prosthesis includes several 3D-printed components as well as a mechanical spring system, which has been designed to mimic the function of a natural canine limb. The upper yellow component acts as an attachment cup or socket that interfaces with the residual limb of the dog. Below the cup, the grey and red linkage assembly represents the two-link articulated joint, which is connected through a pin joint mechanism permitting flexion and extension in a manner that mimics the biological action of a canine knee or elbow joint. The metallic tension spring integrated axially along the joint allows for energy storage during compression and energy release during extension, mimicking tendon-like behavior. The yellow base, a thermoplastic urethane (TPU) paw at the bottom acts as a ground contact pad, providing flexibility, cushioning, and shock absorption during gait.

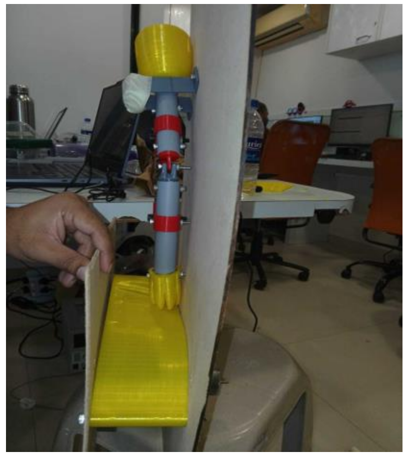

Fig. 3: Bench setup of two-link spring-assisted canine prosthetic limb for testing.

Figure 3 shows the side view of the spring-integrated two-link canine prosthetic limb mounted on a test rig for bench validation and kinematic assessment. The setup helps evaluate the prosthesis's motion, load response, and spring compression during simulated limb movement. The upper yellow socket attaches to the residual limb region, while the articulated joint and spring mechanism in the middle enable controlled flexion and energy return. The lower yellow paw pad, made of flexible TPU, mimics a canine paw for ground contact, cushioning, and impact absorption. The entire prototype is fixed to a vertical support board to ensure stability during testing.

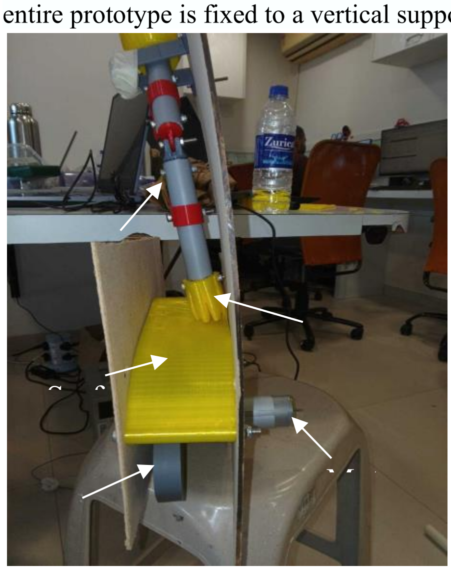

Fig 4. Simulated walking test for a prosthetic leg

The image shows a mechanical test setup designed to simulate the loading conditions experienced by a prosthetic leg during walking. The system consists of a prosthetic leg mounted vertically, with its foot resting on a yellow surface belt. A motor is connected to a cam mechanism that converts rotational motion into a vertical pushing motion. As the motor drives the cam, the cam periodically pushes the surface belt upward, creating a continuous and repetitive loading force at the foot of the prosthetic leg. This simulates the impact and deformation that would occur during real-life walking. The repeated force not only deforms the foot area but also causes movement in the prosthetic leg and its internal spring mechanism, allowing researchers or developers to study the mechanical behavior, durability, and performance of the prosthetic under dynamic conditions. This setup is likely used for testing the effectiveness and resilience of the prosthetic design under simulated walking cycles.

Result & Analysis

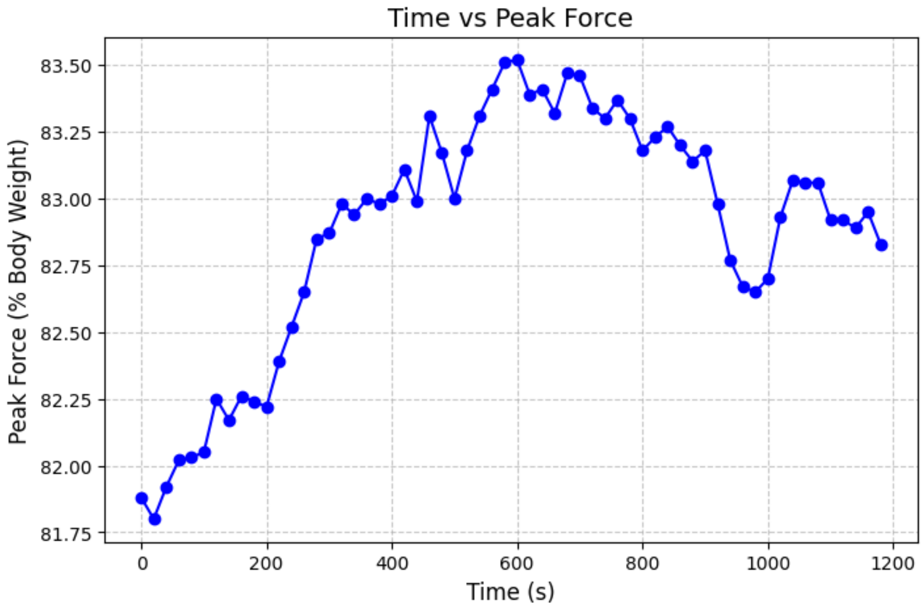

Figure 4: Time vs Peak Force

The chart presents the change in peak ground reaction force with respect to time during the test session of the prosthesis. Time is represented in seconds along the x-axis, while the peak force is expressed as a percentage of the subject's body weight along the y-axis. The peak force begins at nearly 81.8% Body Weight(BW), and then gradually increases, reaching close to 83.5% BW as time progresses, indicating enhanced load transfer and enhanced stability of the system. Following its peak, the force slightly fluctuates and shows a small decrease towards the completion of the test, possibly due to user adaptation, fatigue, or mechanical changes within the prosthetic system. The chart indicates that the prosthesis achieves largely uniform force with low variation over time.

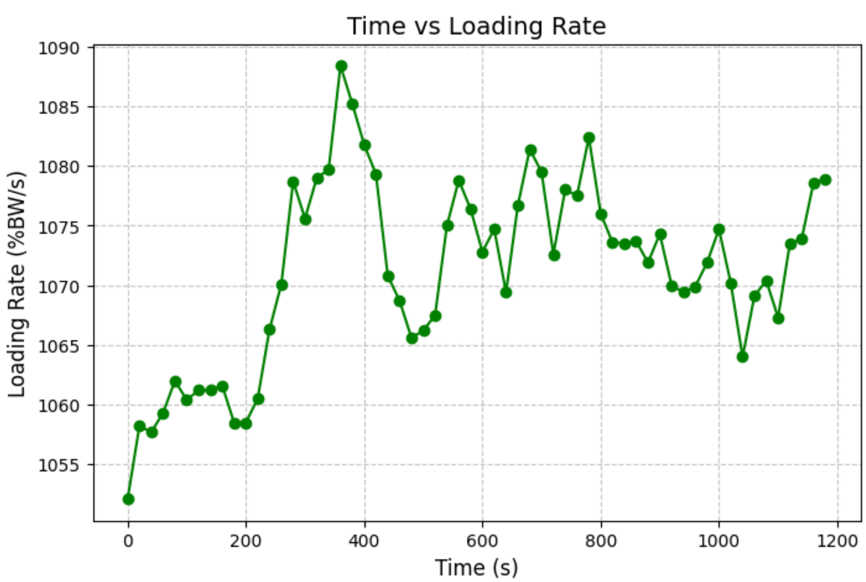

Figure 5: Time vs Loading Rate

The graph "Time vs Loading Rate" illustrates the loading rate (%BW/s) over the span of 1200 seconds. At the onset of the graph, the loading rate is just above 1052 %BW/s and increased steadily with some minor oscillation in the rate during the time-frame. This rate reaches a maximum of approximately 1089 %BW/s at around 380 seconds which could represent a peak load or intensity of activity. Following the peak, the loading rate decreased noticeably. After the decrease, there was a more frequent oscillation across a lower loading rate range of roughly 1065 to 1082 %BW/s. This could suggest the movement from a ramp-up phase to more of a steady or regulated loading phase. The consistency of variability across the second half of the graph could imply a dynamic activity was occurring, or the loading was undergoing more changes to the force being applied. The graph suggests a process that began at lower intensity, increased to a peak intensity, and eventually moved into a more stable sector of recording with some variability.

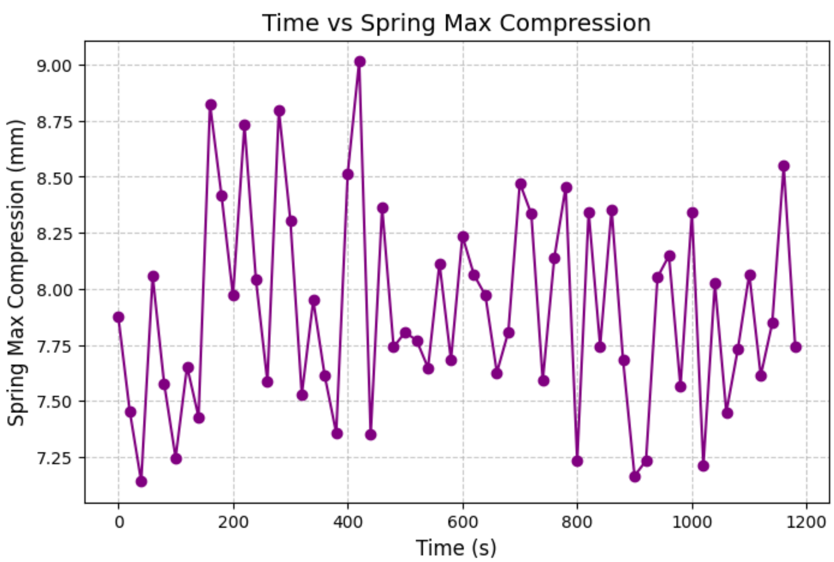

Figure 6: Time vs Spring

The graph labeled "Time vs Spring Max Compression" presents the relationship of maximum compression of the spring (in mm) over a 1200 second time period. At the beginning of the time period, the maximum compression of the spring varied between approximately 7.2 mm and 7.9 mm, indicating some initial variability. After some time, particularly between 200-400 seconds, the spring achieved a higher maximum compression value, reaching a maximum of approximately 9.0 mm around the 400 second timeframe, which is the highest value in the graph. After reaching that maximum, the maximum compression continues to oscillate but, mostly, remain within a slight reasonable range lower than the previous maximum, remaining bounded somewhere in the range of 7.3 mm and 8.4 mm during the latter portion of the time period, neither trending towards a stable dynamic increase or decrease. Thus, the observations suggest activity or force increases for a time initially, which may be a function of ramping load, followed by a steady-state dynamic of bounded outcomes associated with varying loading instance(s) where maximum compression ranges from 7.3 mm and 8.4 mm. The ongoing oscillations indicate an ongoing dynamic load variation or repetitive, dynamic loading similar to some physical element involving springs.

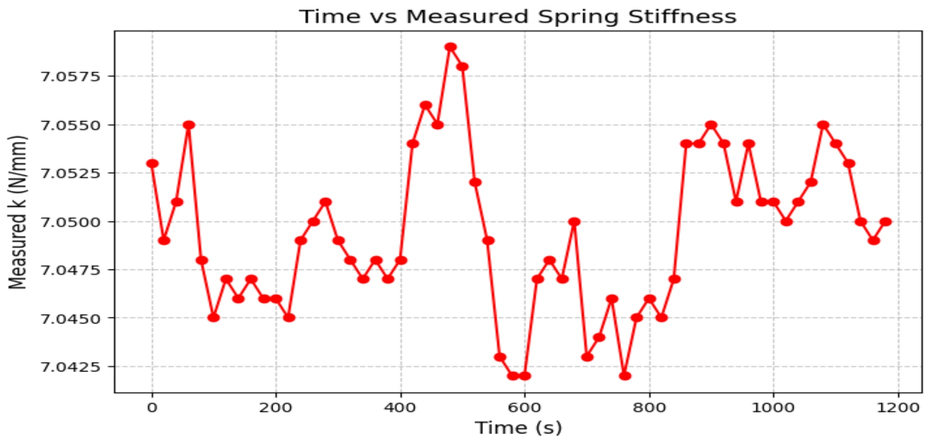

Figure 7: Time vs Measured Spring Stiffness

The graph entitled "Time vs Measured Spring Stiffness" illustrates the change in measured stiffness (k) of a spring over time, with the x-axis representing time in seconds (s) and the y-axis displaying the spring stiffness in Newtons per millimeter (N/mm). The data is plotted as a red line with circular points to indicate the individual measurements taken at designated intervals. The stiffness measurements have some bumpiness and registered averages somewhere around 7.05 N/mm, suggesting some natural variation or noise in measurements, which could be caused by environmental conditions, measurement accuracy, or physical properties of the material. Overall, the measurements are not too far apart, which suggests the spring has fairly constant stiffness for the observation time period of 1200 seconds. The relative stability of the system suggests that it should be reliable in applications requiring the same stiffness.

Conclusion

The current study successfully established, simulated, and validated a spring-integrated two-link prosthetic limb device for restoring structural and dynamic functionality in partially amputated canine limbs. The design, tested through CAD modeling and lab prototypes, showed good mechanical reliability and biomechanical relevance. The prosthesis developed allowed for controlled flexion–extension motion, energy storage and release using stainless-steel tension springs, and replicated natural limb dynamics while mimicking tendon-ligament function.

The experimental validation proved simulation and bench-test measures consistent and closely approximated observed deflection and load behavior. The prototype's design revealed sufficient spring compression and energy return capabilities for measurable mechanical assistance across gait performance, improving stability and load sharing. Finally, the selected materials–PLA, TPU, and PVC demonstrated a reasonable balance of rigidity, flexibility, and cost while establishing a clinically appropriate footing of functionality for veterinary clinical use in India and other settings.

In summary, this study shows that a biomechanically informed, low-cost prosthetic system can also enhance mobility and comfort for canine amputees. Future work should have a focus on in-vivo studies over an extended period of time, gait analysis highlighting the multiple breeds and weight classes, and suspension and socket design refinements to increase comfort and adaptability. The results of this study provide an initial framework for developing prosthetic systems that are affordable, functional, and scalable that can meaningfully advance the rehabilitation and quality of life for canine amputees.

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