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Low-cost Knee Brace Prototype for Rehabilitation After Sports Injury

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Abstract:
The knee brace is a very popular medical device commonly used for rehabilitation and injury prevention of knees. However, conventional knee braces can be very expensive for patients with limited financial resources. Previous study on low-cost knee braces conducted by Alexander Hendricks (2018) only consisted of braces design for Medial Collateral Ligament (MCL) and Lateral Collateral Ligament (LCL) injuries. This paper aims to create a new low-cost knee brace design using 3D printing material that can be used for MCL, LCL and Anterior Cruciate Ligament (ACL) injuries. The proposed design was developed and tested using SolidWorks simulation features. The simulated materials were set similar to the materials of three-dimensional (3D) printing filaments and the dimensions of the knee braces were based upon an actual patient. The results of this study showed that the new designs have been improved in term of Factor of Safety (FOS), due to its adjustable hinges, while the price is much cheaper than conventional knee braces. In conclusion, the aims for this study have been achieved to develop a low-cost knee brace that can be used for MCL, LCL and ACL injuries.

Keywords: Knee Brace; Rehabilitation; Low-cost; 3D Printing; Sports Injury

1. Introduction

Knee injuries are the most well-known musculoskeletal objection to medical services providers. Knee injuries or pain affects approximately 25% of adults. Knee injuries have climbed by approximately 65% in the last 20 years, accounting for nearly 4 million primary care visits each year [1]. The knee is a complicated joint with numerous parts, making it very risky against injury. As a knee joint, the knee is held together by two pairs of ligaments, which have tendons for each side of the knee, known as collateral ligaments, and two ligaments inside the knee, known as the posterior cruciate ligament (PCL) and anterior cruciate ligament (ACL). Both hold the knee bones together and help control the development of the knee [2]. If a person, unfortunately, gets those injuries, they need to undergo surgery and have rehabilitation on post-surgery.

Rehabilitation is care that can assist patients with getting back, keeping, or improving capacities that patients need for daily life. These Abilities might be physical, mental, as well as psychological (thinking and learning). Patients may have lost them due to a sickness or injury, or as a result of medical treatment [3] on the rehabilitation, they also need support to their knee to avoid further injuries, and the supports are orthotics (Knee Brace). There are various types of knee braces, the first is the unloader knee brace which is usually used by osteoarthritis sufferers to help relieve pain, the second the prophylactic knee brace is usually used to protect a healthy knee from injury, the third is the functional knee brace is usually used to provide stability to the less stable knee ligament, and the last is the patellofemoral knee brace which is usually used for anterior knee pain [4].

One common injury is the knee joints injuries, which are reformed using knee braces, but unfortunately for rehabilitative knee braces with good quality for Anterior Cruciate Ligament (ACL), Medial Collateral Ligament (MCL), meniscus, and arthritis have cost average of $100 until $900 which make this device as expensive in term of recovery devices and it is non-affordable for some patients even though these devices are used to support rehabilitation [5]. This study is based on a study from Hendricks et al. [6] which study to design low-cost knee orthotics but faced some problems on design and material which this study tried to solve it.

This study aims to find solutions to some of the problems present in the previous paper [6], the design of low-cost knee braces previously can only be used by people with MCL and Lateral Collateral Ligament (LCL) injuries, this study was conducted to design experiments that can also help people with ACL. Next, the selected material was less strong previously. Lastly, the expensive cost of making a knee brace with custom size with an average price of about $740 [7].

2. Materials and Methods

The methods that have been used in this study is 3D designing using Solidworks software. This study has created three types of 3D designs with different models, the following steps have been taken to achieve these goals; Design planning in 2-Dimension sketch; 3D modelling sketch; Material selection; Finite Element Analysis (FEA) simulation to determine if the brace is strong enough to handle the knee and leg forces; Steps repetition for other designs; Analyze and compare all designs.

The size of the design [8] and force applied have been carried out which are measured from the actual patient and the value has been set as written in Table 1 and Table 2. The points where the forces were applied is following the study by Hendricks et al. [6] which shown in Figure 1.

Table 1. Size of brace

	Calf	**Thigh**
Length from the knee	5 - 10 cm (Below the knee)	10 - 15 cm (above the knee)
Size (round)	13.7 in / 35 cm	16.9 in / 43 cm

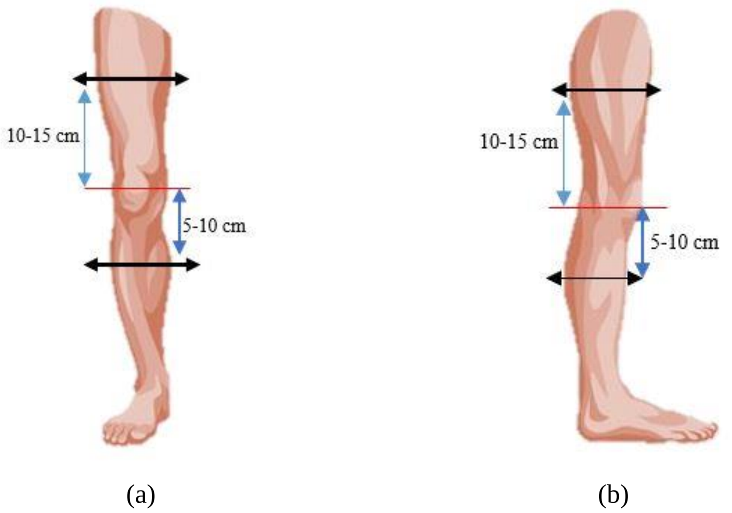
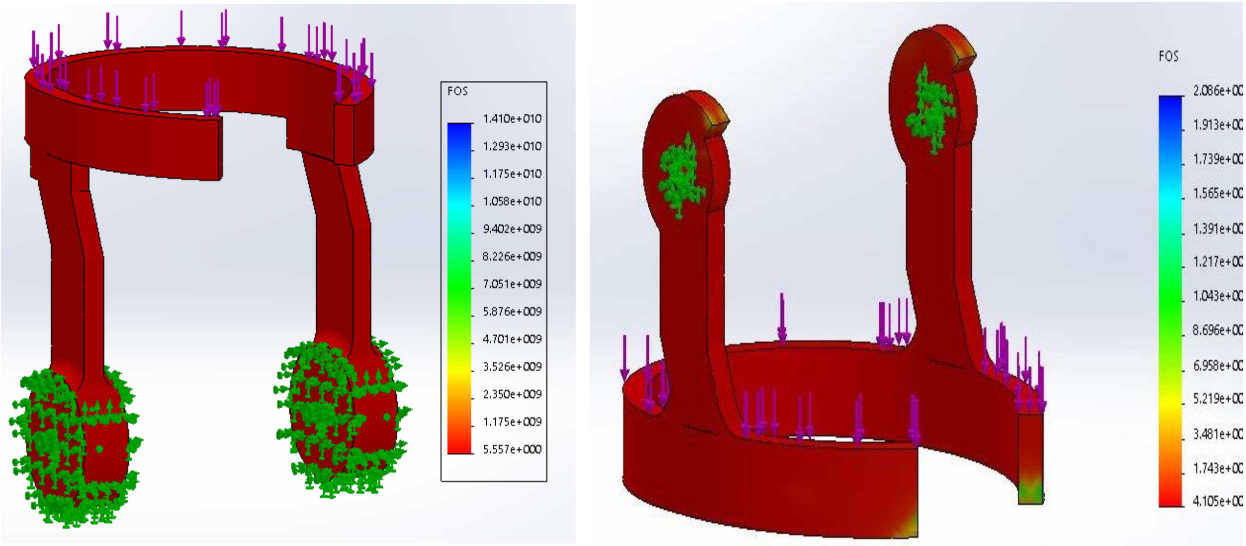


Figure 1. The measurement of knee brace: (a) Front view and (b) Side view

Table 2. Force applied on FEA

Parts	**Force Applied**
Upper brace	143.3 lbf (637.43 N)
Lower brace	143.3 lbf (637.43 N)



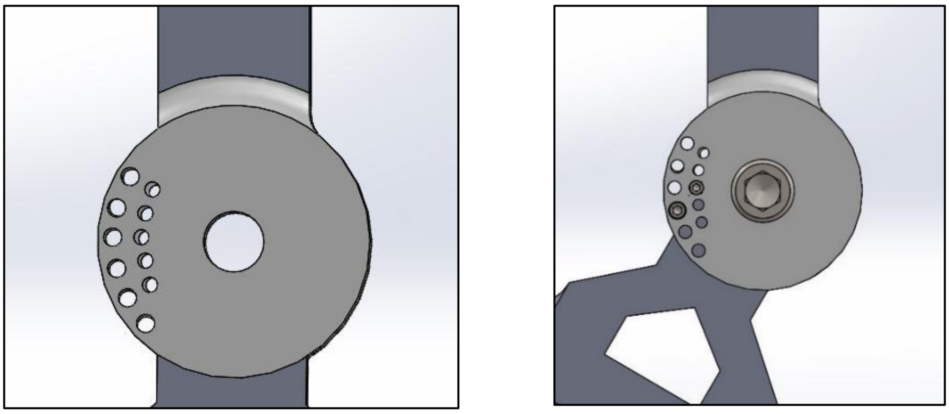
(a) (b)

Figure 2. Points of force applied on design (a) upper brace and (b) lower brace

Material is very important; it determines the quality and strength of the design [9]. 3D printing methods facilitate innovation which will speed up production while decreasing expenses [10], therefore this study will simulate four types of material made of plastic (3D filament). The reasons for selected material are easy to get and found in the market for experiment and authors needed more than one material for comparisons and to decide which design of brace using what material is the best. The materials that have been used in this study were polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polypropylene and polycarbonate.

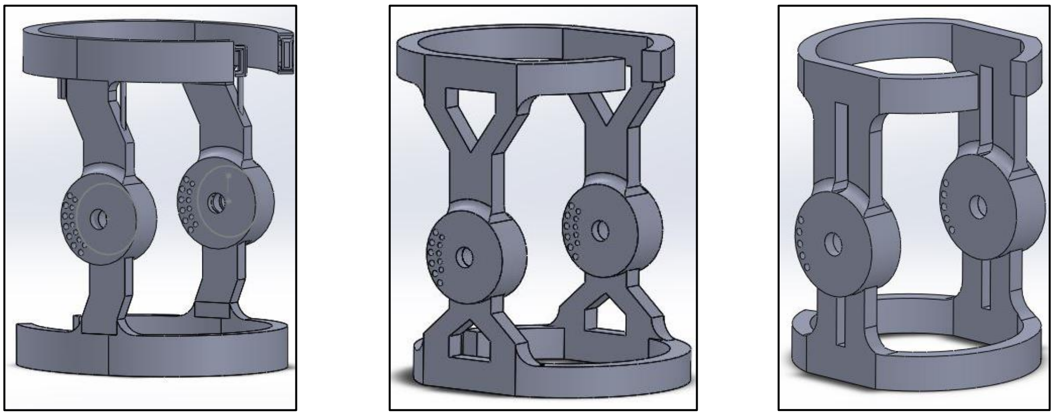
3. Results and Discussion

The following Figures (Figure 3 and 4) and Tables (Table 3 – 7) display the result of simulations and calculated cost on three different knee braces models. Comparison for each design will be done after FEA simulation, to decide which design is the best.



(a) (b)

Figure 3. Proposed hinges: (a) Adjustable hinge and (b) adjustable hinge with bolt and nuts



(a) (b) (c)

Figure 4. Proposed knee brace: (a) Design 1, (b) Design 2 and (c) Design 3

Table 3. FEA results of PLA material

	Von Misses Stress (ksi)	Displacement (in)	Factor of Safety	Cost ($)
Upper brace				
Design 1	8.061×10^{-1}	$3.369\times10\text{-}^{2}$	4.7	17.70
Design 2	5.013×10^{-1}	2.803×10^{-2}	7.5	20.63
Design 3	6.824×10^{-1}	2.463×10^{-2}	5.5	15.83
Lower brace				
Design 1	$9.216\text{x}10^{-1}$	$4.726\times10\text{-}^{2}$	4.1	12.58
Design 2	$8.369\text{x}10^{-1}$	4.217×10^{-2}	4.5	15.41
Design 3	1.047	4.165×10^{-2}	3.6	9.33

Table 4. FEA results of ABS material

	Von Misses Stress (ksi)	Displacement (in)	Factor of Safety	Cost ($)
Upper brace				
Design 1	8.134×10^{-1}	5.961×10^{-2}	3.3	16.23
Design 2	5.013×10^{-1}	4.927×10^{-2}	5.3	18.92
Design 3	6.190×10^{-2}	4.338×10^{-2}	3.9	14.71
Lower brace				
Design 1	9.301×10^{-1}	3.277×10^{-2}	2.9	11.53
Design 2	8.340×10^{-1}	7.422×10^{-2}	3.2	14.13
Design 3	1.058	7.338×10^{-2}	2.5	8.56

Table 5. FEA results of polypropylene material

	Von Misses Stress (ksi)	Displacement (in)	Factor of Safety	Cost ($)
Upper brace				
Design 1	7.554×10^{-1}	6.154×10^{-2}	8.3	12.15
Design 2	5.026×10^{-1}	5.545×10^{-2}	12.0	14.17
Design 3	6.357×10^{-1}	4.735×10^{-2}	9.8	10.90
Lower brace				
Design 1	8.729×10^{-1}	8.828×10^{-2}	7.1	8.64
Design 2	8.203×10^{-1}	8.237×10^{-2}	7.6	10.59
Design 3	9.892×10^{-1}	8.015×10^{-2}	6.3	6.41

Table 6. FEA results of polycarbonate material

Upper brace				
	Von Misses Stress (ksi)	**Displacement (in)**	**Factor of Safety**	**Cost ($)**
Design 1	$8.059\times10\text{-}^{1}$	3.38×10^{-2}	13.0	25.59
Design 2	5.013×10^{-1}	3.023×10^{-2}	20.0	29.83
Design 3	$6.821\times10\text{-}^{1}$	2.660×10^{-2}	15.0	22.35
Lower brace				
Design 1	9.213×10^{-1}	5.103×10^{-2}	11.0	18.19
Design 2	8.369×10^{-1}	4.554×10^{-2}	12.0	22.30
Design 3	1.046	4.498×10^{-2}	9.7	13.49

Table 7. Estimated costs

Comparison (Cost) – in USD ($), Previous Design = 37.53				
	PLA	**ABS**	**Polycarbonate**	**Polypropylene**
Design 1	32.44	29.92	45.94	22.95
Design 2	38.21	35.21	54.29	26.91
Design 3	27.32	24.43	38.00	19.47

Based on Figure 1 and Figure 2, Design 1 is a design that prioritizes futuristic visuals, and it obtained the Factor of Safety (FOS) value above Design 3 which is assumed that the more foundations/bars, the stronger/better the simulation results, however the simulation results show the opposite. In contrast to Design 2, the design follows the design of existing medical devices or assistive technology, namely crutches. Crutches are designed to follow a 3-point force system, which is where the 3-point force system itself has a definition; a system which one main force acting in one direction and other two forces working in the opposite direction to maintain balance in the force system. This system is the reason why Design 2 has a higher value factor of safety compared to Design 1 and Design 3.

In terms of cost in Table 3, Table 4, Table 5 and Table 6, polycarbonate has the highest cost, because for the price of the raw material, Polycarbonate has a difference of around $8 when compared to other materials that has been selected. Actually, the price of raw material for the same filament with a size of 1.75mm has a variety of prices, some are cheap and some are expensive. The difference in raw material prices has the main reason, namely brands, top brands such as HatchBox and also E-sun have relatively higher prices when compared to other cheaper brands such as CCTREE.

Based on FOS and data comparison as well, the previous study design showed a significant difference in FOS compared to the new design, and after further study and search the researcher found that the previous study missed input on the yield strength value. Yield strength maximum value in Polylactic Acid (PLA) material should be at a value of 103 MPa or equivalent to 14.9 ksi, while the previous study included a value of 580.2 ksi or equivalent to 4000 MPa. For example, for stainless-steel 316 the material only has a yield strength of 42.06 ksi or equivalent to 290 MPa. As we know PLA is a plastic material, which means it inputs a plastic yield strength value of about 14x greater than steel material. For this reason, the researcher cannot make a comparison between the new design and the previous study design in the term of FOS.

On the cost factor, as shown in Table 7, it shows that the cost for the new design is cheaper than the previous study design, even after the new design is equipped with straps and foam, it becomes a ready-to-use low-cost knee brace and an additional adjustable hinge feature as well. has been implemented in the new design.

From the simulation results stated in shown tables, Polycarbonate and Polypropylene have more strength when compared to the other 2 materials such as PLA and ABS. Also, estimated cost Polycarbonate has a cheaper price with an average difference of $100 for each design. In the design comparison, it also shown that Design 2 has an average FOS value above Design 1 and Design 3. So, it can be concluded that Design 2 using Polypropylene material is the best choice in this study.

4. Conclusion

In conclusion, developed design offers new features (in low-cost knee brace model) as compared to latest study design, the knee brace or the design now could use for rehabilitation not only for MCL and LCL injury but also for ACL injury because of its adjustable hinge. The price also decreases and still below $100 which is the target. Improvements can still be made in the future study/experiment. Adjustable hinge needs to be tested if its strong enough to handle patient's weight. next, Medical CAD software can be used to improve the accuracy of the design. Next, composite material can be used for stronger brace as on this study only use material which available on the market. Lastly, printed design may help to know on how the design actually work.

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