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Conceptual Design and Analysis of a Hybrid Walking Cane

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Abstract - **This work is aimed to design and analyze the staircase climbing aid, hybrid with the function of walking cane. The tremendous demand for living space increases the essentiality of staircase, corresponding to the escalation of fall injuries. The handrails complemented along with staircase had provided deficient safeguard for staircase user, particularly senior citizen and people with lower limb disability, who need staircase climbing aid to provide extra support during escalating or declining staircase.**

Keywords — ANSYS, conceptual design, hybrid, material selection, staircase climbing aid, walking cane.

I. Introduction

In this time of globalization and urbanization, the inclination in demand for living space motivates the application of staircase, as it presents as the primary alternative for space limitation issue [1]. With an identical dimension of land, the existence of staircase enable building to be construct upward to create more living space compared to landed house, for instance the apartments and landed houses. Despite the convenience of staircase application, it commits to the fall injury circumlocutorily [2]. The handrails complemented along with staircase provides deficient safeguard to users, by the reason of it only provides support for one hand to prevent fall over the side or backward. The installation of elevator serves as second option for transition between floors, however, it is not preferred due to the relatively high cost for installation and space requirements [3].

Miscellaneous type and form of staircase climbing aid product are available in current healthcare market. Staircase climbing wheelchair appears as the most broadly use staircase climbing aid, as it could meant for both users with or without remained strength on their upper body. Staircase climbing wheelchair that are available in current market were categorized into immotile form and mobile form. A mobile staircase climbing wheelchair is portable to carry around, for instance the TGR Scoiattolo 2000, TopChair-S EPW-SC, and Independence iBOT 4000 Mobility System [4–8]. The wheelchairs mentioned are powered by battery, however, the TopChair-S and Independence iBOT 4000 Mobility System are occupant-operated stair climbing wheelchairs that are used autonomously by users, while the TGR Scoiattolo 2000 is classified as assistant-operated stair climbing, which requires manual assistant during application. The immotile staircase climbing wheelchair is the type of wheelchair that requires specific track to move, which is also well-known as stairlifts. Stairlifts are mounted on wall of users' living space and it required rail or track to move along the wall [9-10]. The existing product for such form of staircase climbing wheelchair was developed by Bruno Independent Living Aids in USA, which is known as the Elan Stairlift [11]. The hulking size of a staircase climbing wheelchair leads to one of the limitations in usage, as the storage of the staircase climbing wheelchairs may occupy a certain space when not in use.

Exoskeleton is a set of simulated human exoskeleton that can be wear on a human's body to provide user support and protection on lower limb [12]. Hence, the application of exoskeletons is further implementing in the field of healthcare and rehabilitation. A wearable hybrid orthosis is the hybrid system of exoskeletal brace consists of electrical and mechanical techniques and knowledge in restoring functional movement of lower limbs, it has evolved into a well-known development in walking assistant device for elderly, instead of targeting on people with leg disability [13]. Honda Motor Co., Ltd has released a commercialized hybrid orthosis, known as Walking Assist Device with Stride Management Assist [14]. ReWalk Robotics also announced a wearable exoskeleton, which is ReWalk 6.0 Personal System [15]. The Walking Assist Device with Stride Management Assist is much compact and light-weighed compared to the ReWalk 6.0, as the ReWalk 6.0 is meant for user with totally disability in lower limb. A hybrid orthosis serves as the best option for people who lost their ability in independent walking, however, the high complexity in the construction of an exoskeleton causes increment in both initial and maintenance cost, the selling price and maintenance cost is not favorable by moderate-income users.

The most common staircase climbing aid appeared in support form, which enable user to employ the strength of their hand in providing themselves extra support during the escalation or declination of staircase. StairSteady that was invented by Ruth Amos and released by StairSteady Ltd. is one of the existing products under the classification of staircase climbing aid support [8].

Thus, in order to overcome the limitations in term of space saving, consumability and mobility of a staircase climbing aid, the concept of staircase climbing support is implemented in the design and development of the hybrid staircase climbing aid. The current work is aimed to design and analyze the staircase climbing aid, hybrid with the function of walking cane.

II. MATERIALS AND METHODS

A. Conceptual Design

Three preliminary designs were hand sketched with tentative parameters. The concept of these three designs were constructed based on the structure of a Vernier callipers. The gap between the two clamps is adjustable in order to lock the clamp on the handrails of staircase during staircase climbing. The finalized preliminary designed was selected as illustrated in Fig. 1, by applying the scoring method as shown in Table I.

Design selected had applied the function of gas spring in moving the clamp. Gas spring is a spring mechanism relies on elastic deformation using compressed gas consisted within an enclosed cylinder [16]. The upper clamp of this design was fixed as a common hand grip, which covered by adhesive type of materials, grippy but not sticky, for gripping purpose. The moveable lower clamp was attached to one end of the gas spring, the other end of gas spring was lock at the lower bar by using bolt and nut. Users only required to pull the clamp backward and release when locking onto the handrails. The gas spring will push the clamp and lock it on the handrail due to its elastic characteristic. The lower clamp was covered with adhesive materials also, to increase the friction between the contact surface of clamp and handrails. Torch light was attached to the hand grip, and stopper with larger area was attached at the end of the walking cane to prevent slip when in contact with ground.

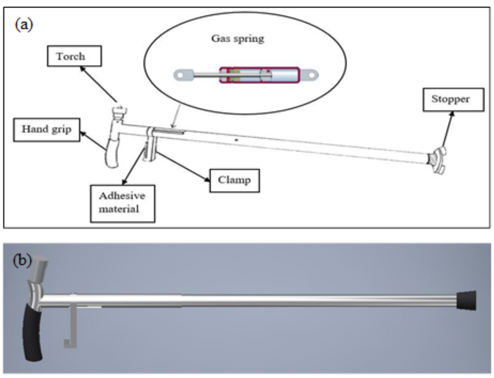

Fig. 1. Preliminary design of prototype - Design C, (a) sketching, (b) 3D model drawing.

Table I. Concept Scoring of Preliminary Design A, B and C.

		Design A		Design B		Design C	
Selection Criteria	**Weight**	***R**	**Score**	***R**	**Score**	***R**	**Score**
Flexible of use	30						
Use in different situation	15	3	0.45	1	0.15	5	0.75
Hold different handrails	15	5	0.75	1	0.15	5	0.75
Ease of manufacture	20						
Low complexity of parts	10	4	0.4	2	0.2	4	0.4
Low number of assembly steps	10	3	0.3	2	0.2	3	0.3
Ease of use	20						
Usable with one hand	3	3	0.09	1	0.03	4	0.12
Can use without complex guide	6	3	0.18	2	0.12	4	0.24
Comfortable to grip	5	3	0.15	3	0.15	3	0.15
Does not slipped	6	4	0.24	4	0.24	4	0.24
Portability	10						
Easy to carry	6	3	0.18	2	0.12	4	0.24
Occupied least space	4	3	0.12	2	0.08	4	0.16
Cost	20						
Low number of parts	8	3	0.24	2	0.16	4	0.32
Low cost materials	8	3	0.24	3	0.24	3	0.24
Low maintenance required	4	3	0.12	1	0.04	5	0.2
	Total score		3.46		1.88		4.11
	Rank		**2**		**3**		**1**

*Note: ***R*** = Rating

B. Materials Selection

The materials, mechanism and components involved were selected via screening method and scoring method. The materials and component selected in completing the prototype design shall fulfilled the requirements of high strength, light-weighted and affordable.

The hybrid walking cane designed had combined the function of a staircase climbing aid, hence the product is a beam when it is used as staircase climbing aid, and a column when it is used as walking cane. Hence, when referring to the chart of Young's Modulus against density, the guide lines referred was respect to minimum weight design of stiff beams, shafts and columns, as shown in [17, Eq. (1)] below.

$$C = E^{1/2}/\rho \tag{1}$$

where C is the minimum weight design of stiff beams, shaft and columns, E is the Young's Modulus in Pa and ρ is the density required in kg/m^3.

Density required was between 2 to 3 milligram per cubic metre (mg/m^3). In order to determine the required range value of Young's Modulus, Euler's equation for column was rearranged with respect to expected load, P [17, Eq. (2)]. The column was expected to withstand load of 80 to 100 kg, which are approximate to 800 N and 1000 N respectively. Thus, the column shall made of materials with Young's Modulus between 100 GPa to 300 GPa.

$$E = (PL^2)/(\pi^2 I) \tag{2}$$

where E is the Young's Modulus in unit GPa, I is the moment of inertia of cross section that resist the direction of buckling in m^4 or mm^4, L is the effective length of the structure and P is the expected load in Newton (N) [17].

The region of Young's Modulus required was marked in blue colour, while the density was marked in green colour as shown in Fig. 2, the materials with greater stiffness-to-weight ratio lie towards upper left-hand corner. Engineering alloy was chosen instead of porous ceramic or engineering ceramics, due to the accessibility and practicability of the product design. Besides, the ductility of metals is higher than ceramics materials [18]. By observing the selected potential area, there were several materials that were considered, which are copper alloys, aluminium alloys, stainless steel, titanium alloys, cast iron and mild steel.

Titanium alloy is not common in current metal market and it is costly as comparing to other potential metals. Hence, titanium alloy was excluded due to its difficult accessibility. Scoring method was applied for further selection analysis as shown in Table II. The result of scoring had shown that aluminum alloys is the material that fulfilled the requirements to develop the hybrid walking cane.

Table II. Scoring Table of Material Selection.

Selection Criteria	Weight	Material					
		Aluminium Alloy		Stainless Steel		Mild Steel	
		*R	Score	*R	Score	*R	Score
Cost	20%	3	0.60	2	0.40	5	1.00
Density	20%	5	1.00	2	0.40	2	0.40
Elastic moduli	20%	3	0.60	4	0.80	4	0.80
Wear	15%	5	0.75	4	0.60	1	0.15
Fatigue endurance limit	15%	3	0.45	4	0.60	4	0.60
Machinability	10%	3	0.30	4	0.40	4	0.40
Total Score			**3.70**		**3.20**		**3.35**
Rank			**1**		**3**		**2**

*Note: ***R*** = Rating

C. Ergonomics Considerations

The length of the hybrid walking cane is determined by considering the most comfortable gripping distance that can maximize the gripping strength via ergonomics survey and studied done, meanwhile the width of hallway and stairs also taken into consideration regarding the hybrid walking cane was targeted to be apply in both vertically (as walking cane) and horizontally (as staircase climbing support) [20-24]. Several useful features will be embedded in the hybrid walking cane, such as torch light equipped at the head of the crutch to enable user to walk in dark, stopper fixed at the end of the crutch to prevent slipping, as well as extendable bar to be adjust according to different users' height.

D. Bending Moment and Shear Stress Analysis

The hybrid walking cane serves as both staircases climbing aid and walking cane. Hence, analysis was carried out by simulating the product design as both cantilever beam and column, to determine the safety factor, maximum allowable shear stress of each parts, maximum bending moment of the walking stick and its respective location of force applied.

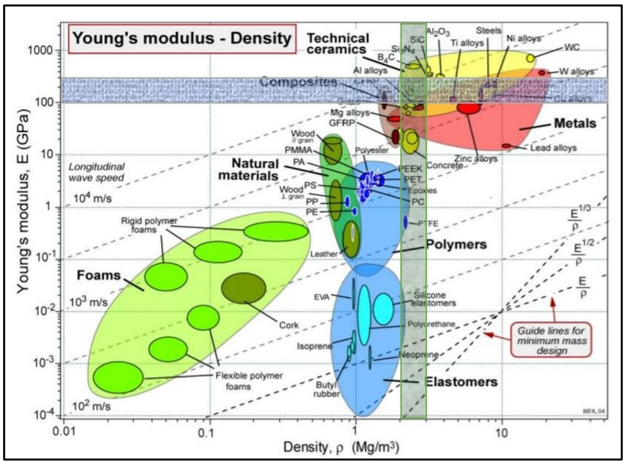

Fig. 2. Graph of Young Modulus against density [19].

The type of beam was selected as cantilever beam as the walking cane was fixed at one end when clamping on a handrail to be used as staircase climbing aid. The analysis was accomplished based on force applied in downward direction, as shown in Fig. 3 below, due to its critical level when compared to the force applied upward or backward.

The gap between handle and clamp was set as fixed point, as circled in red. The total length of beam was 0.64 meter, counted from the fixed point as circled in Fig. 3(a) to the end of the walking cane. The schematic diagram for real life application of staircase climbing aid as shown in Fig. 3(b). Hand gripping force of both hands were assumed as distributed load. There were three possible locations for users to grip, which are 0, 0.075 m and 0.275 m towards left away from the most end of the cane. The variation of bending moment and shear stress were computed by inspecting four portions of cuts on the beam, as illustrated by dash line with respect to '*a*', '*b*', '*c*' and '*d*' in Fig. 3(c).

The values of internal moment and reaction force of the entire beam were calculated by treating entire beam as rigid body, thus total summation of moment and reaction force were equal to zero, as shown in Eq. (3) and Eq. (4) below.

$$\sum M = 0 \tag{1}$$

$$\sum F_y = 0 \tag{2}$$

where M is the moment in N.m and F_y is the reaction force in y-direction, with the unit N.

The internal moment and reaction force were further derived by substituting the value extracted from Fig. 3, as shown in Eq. (5) and Eq. (6) below.

$$M_o = \omega_1 L_1 [\frac{L_1}{2} + (L_4 - L_1 - L_3 - L_2 - A)] + \omega_2 L_2 [\frac{L_2}{2} + (L_4 - L_2 - A)] \tag{3}$$

$$R_y = \omega_1 L_1 + \omega_2 L_2 \tag{4}$$

where M_o is the internal moment in N.m, Ry is the reaction force in *y*-direction with the unit of N. The fixed unit involved in the equations was mentioned and explained in Table III. ω is the distribution load representing hand grip on the walking aid in Newton per meter (N/m), F is the concentrated force converted from the distribution load in unit Newton (N), while L indicated the length in meter (m). Unknown value 'A' represented the distance of gripping position from the end of walking cane.

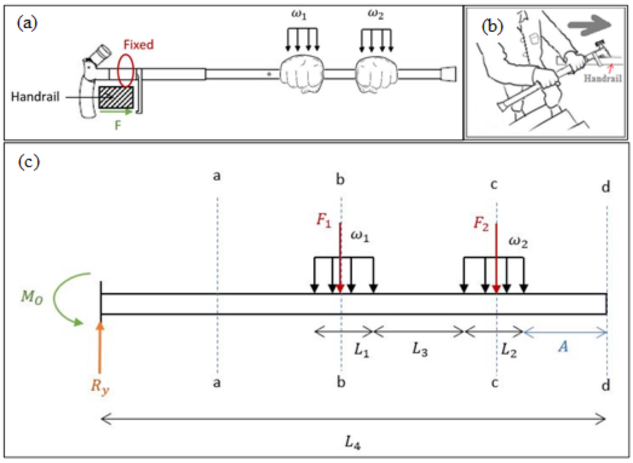

Fig. 3. (a) Schematic diagram of staircase climbing aid, (b) staircase climbing aid in used, and (c) free body diagram as a cantilever beam.

Table III. Fixed Value for Cantilever Beam.

Fixed value	Value	Unit	Remarks
$\omega_1 = \omega_2$	400.00	N/m	Average weight of elderly (Distributed load)
$F_1 = F_2$	32.00	N	Average weight of elderly (Concentrated force)
$L_1 = L_2$	0.08	m	Average palm width of elderly
L_3	0.20	m	Ideal distance of grip
L_4	0.64	m	Total grip-able length of walking stick

The moment computed was indicated in M with respect to cutting position, in Newton-meter (N.m), M_o is the internal moment of entire beam in Newton-meter (N.m), 'V' represented the shear force variation and R_y is the reaction force in *y*-direction, both values computed in unit Newton (N). [25-26]

E. Bending Moment and Shear Stress Detailed Calculation and Its Equations

The calculation for moment as aforementioned was carried out based on illustration sketched, sectioning free-body-diagram as shown in Fig. 4 to Fig. 7 and their respective equations as presented in Eq. (7) to Eq. (14).

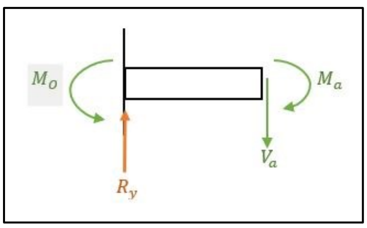

Fig. 4. First cut regarding to '*a*'.

$$\mathrm{M_a} = \mathrm{M_o} \tag{5}$$

$$\mathrm{V_a} = \mathrm{R_y} \tag{6}$$

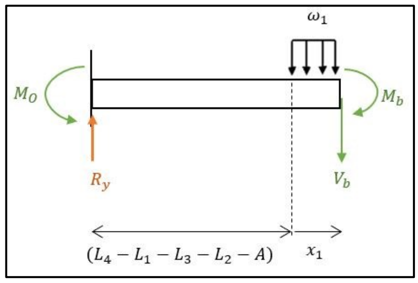

Fig. 5. Second cut regarding to line '*b*'.

$$M_b = M_o - \omega_1 x_1 \left(\frac{x_1}{2}\right) - R_y(L_4 - L_1 - L_3 - L_2 - A + x_1) \tag{7}$$

$$V_b = R_y - \omega_1 x_1 \tag{8}$$

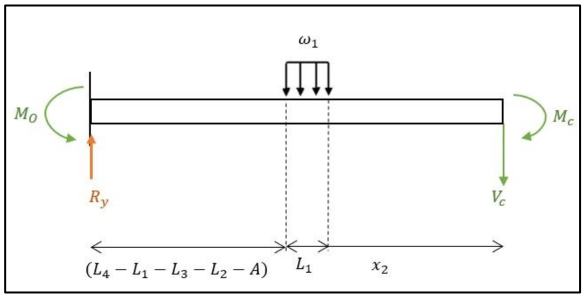

Fig. 6. Third cut regarding to line '*c*'.

$$M_c = M_o + \omega_1 L_1 \left(\frac{L_1}{2} + x_2\right) - R_y(L_4 - L_3 - L_2 - A + x_2) \tag{9}$$

$$V_c = R_y - \omega_1 L_1 \tag{10}$$

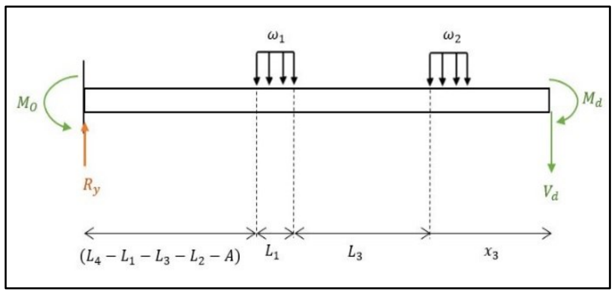

Fig. 7. Forth cut regarding to line '*d*'.

$$M_d = M_o + \omega_1 L_1 \left(\frac{L_1}{2} + L_3 + x_3\right) - \omega_1 x_3 \left(\frac{x_3}{2}\right) - R_y(L_4 - L_2 - A + x_3) \tag{11}$$

$$V_d = R_y - \omega_1 L_1 - \omega_1 x_1 \tag{12}$$

Three sets of data shared the same pattern in shear stress and bending moment analysis. The shear force diagram was illustrated in Fig. 8(a), it can be seen that each of the length of gripping experienced decreased as the distance increased toward the free end of beam, and stopped at the same value of 65.60 N, due to the balance of the moment in the entire beam system. The maximum bending moment occurred at the value of 29.85 Nm as indicated in Fig. 8(b), the variation of bending moment at three different value of '*A*' had same pattern, the line increased as the gripping location nearer to the end of the walking cane.

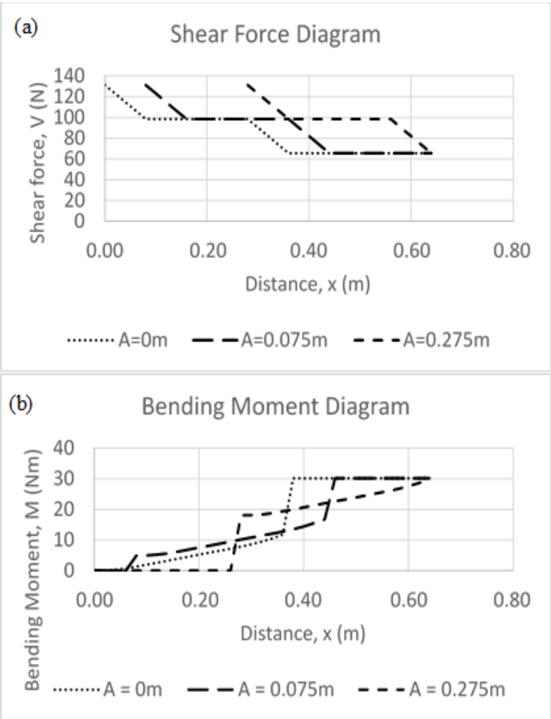

Fig. 8. (a) Shear force diagram and (b) maximum bending moment diagram.

F. Critical Buckling Load Analysis

Hybrid walking stick acts as a column when it is used as walking stick instead of staircase climbing aid. Hence, calculation for column was applied to determine the critical buckling load and critical stress of walking cane, specifically Euler's formula for pin-ended columns [17, Eq. (15) - (16)].

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{13}$$

$$\sigma_{cr} = \frac{P_{cr}}{A} \tag{14}$$

where P_{cr} represents the critical buckling load in N, σ_{cr} is the critical stress in Pa, E is the Young's Modulus in unit GPa, I is the moment of inertia of cross section that resist the direction of buckling in m^4 or mm^4 [17, Eq. (17)], L is the length of the structure and A is the cross sectional area in m^2 [18].

Due to the end condition of walking cane was fixed as shown in Fig. 9, the effective length equals to twice the length of structure [17, Eq. (17)]. As for the moment of inertia, the structure was a cylindrical member, hence the buckling only occurred in one axis [17, Eq. (18)], where L_e is the effective length in meter (m), and L is the length of the structure in meter (m); and D_o is the outer diameter and D_i is the inner diameter of the cylindrical members in meter (m).

$$L_e = 2L \tag{15}$$

$$I = \frac{\pi}{64}(D_o{}^4 - D_i{}^4) \tag{16}$$

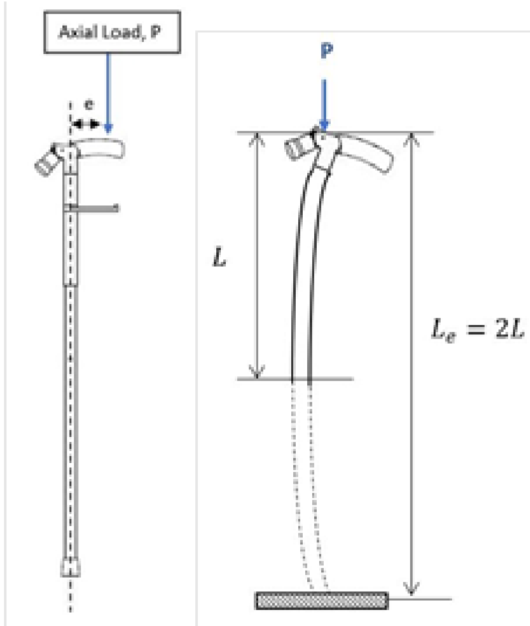

Fig. 9. Effective length of one fixed end and one fixed end column.

Critical load of 1.626 kN was calculated by substituting Young's Modulus of Aluminium Alloy 6061 (E = 200 GPa [19]) and the total length of walking cane (L = 0.835 m). The expected load was 1 kN, which is equal to the expected weight of users with 100 kg. The critical load computed was greater than expected load, hence the column will not fail [18]. For the column to remain elastic, the critical stress, σ_{cr} must be less than the yield stress of column material [19]. The critical stress of walking cane designed was 28.75 MPa, which is smaller when compared to the yield stress of Aluminium Alloy 6061, 275 MPa, thus the walking cane was able to remain elastic.

G. Critcal Buckling Load Detailed Calculation and Its Equations

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

$$E = 200GPa, L = 0.835\text{m}$$

$$L_e = 2L = 2(0.835\text{m}) = 1.67\text{m}$$

$$I = \frac{\pi}{64}(D_o{}^4 - D_i{}^4) = \frac{\pi}{64}(0.019^4 - 0.017^4)$$
$$= 2.2973 \times 10^{-9}\text{m}^4$$

$$P_{cr} = \frac{\pi^2(200 \times 10^9)(2.2973 \times 10^{-9})}{(1.67)^2} = 1.626\text{kN}$$

$$P = 1000N = 1\text{kN}$$

$$\sigma_{cr} = \frac{P_{cr}}{A}$$

$$A = \pi(r_o{}^2 - r_i{}^2) = \pi(0.0095^2 - 0.0085^2) = 56.5487 \times 10^{-6}\text{m}^2$$

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{1.626 \times 10^3}{56.5487 \times 10^{-6}} = 28.75\text{MPa}$$

$$Yield\ stress\ of\ Aluminium\ 6061\ T6 = 275\text{MPa}$$

H. Simulations

The walking cane model was simulated in both cantilever beam and column condition using Autodesk Inventor Professional 2019. The final outcome of simulation consisted of safety factor, maximum shear stress, as well as displacement of the model.

The surface of hand grip and clamp was fixed to illustrate the locking motion of handrail during the usage of the hybrid walking cane as a staircase climbing aid. A force of 373.1 N was applied on the lower clamp towards right, indicating the force reacting when a handrail was locked on as shown in Fig. 10(a). Face split was done on the cylindrical rod to apply the resultant forces. Two concentrated force with 32 N each was applied on the most critical gripping position that leads to maximum bending moment. The value of 32 N was the result of converting 400N of distributed load into concentrated load that indicating the hand grip force of users as shown in Fig. 3 aforementioned.

The walking cane was used in vertical form; hence it is a one fixed end with one free end column. To simulate the condition, the walking cane was fixed at the bottom, a force of 750 N was applied on the hand grip as shown in Fig. 10 (b), the value of 800 N indicating the expected load (weight of users) of walking cane. Despite the expected load discussed in critical buckling load analysis above was 1000N, which is 100 kg respectively, however, users were expected not fully lean towards the walking cane when use, since they are still able to walk on their own, hence 750 N was used for simulation purpose. The target outcomes for this simulation were maximum value of Von Mises stress, maximum displacement and the safety factor.

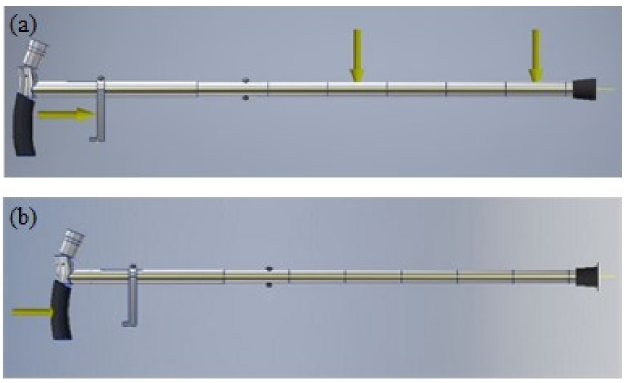

Fig. 10. (a) Deformation analysis at most critical gripping position and (b) buckling load analysis for column using Autodesk Inventor Professional 2019.

The clamp serves as the crucial component in defining the practicability of the entire design, thus, simulation was carried out on part of clamp individually by using ANSYS 19.0, due to the advantage of ANSYS 19.0 in simulating smaller node size precisely. Force applied for stress analysis on clamp was determined by computing maximum bending moment, since the maximum bending moment is equal to the product of force applied and distance from the end of clamp to the point of moment [9, Eq. (19)], where M_{max} is the maximum bending moment in unit of Newton-meter (Nm), F is the force applied in Newton (N) and x is the distance from the end of the clamp to the point of moment concerned in meter (m).

$$M_{max} = Fx \tag{17}$$

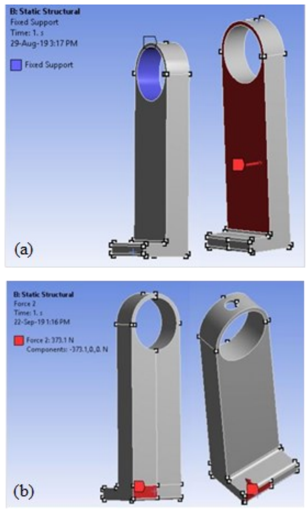

Fig. 11. Deformation analysis using ANSYS 19.0 for resultant force applied at (a) the surface of clamp and (b) both side of clamp edge.

The force computed with respect to the maximum bending moment of entire beam was 373.1 N. Simulation was accomplished for two of the possible moment reactions that leads to greatest critical impact. Figure 11(a) had shown the resultant force applied on the surface of clamp, while Fig. 11(b) indicated the reaction moments from opposite direction when the clamp was locking on the handrail. To further investigate the relationship of the loads and their respective von-mises stress and maximum displacement, the force applied was varied from 100 N to 500 N, aside of the resultant force defined in previous section. Due to the computed resultant force was 373.1 N, hence the value that smaller and greater than the resultant force were applied to indicate the effect on the maximum Von-mises and maximum displacement.

I. Design Optimization

In order to further improve the light-weight characteristic on the product design, design optimization was executed. The part of design to be optimized was targeted on the thickness of clamp. The relationship of load variation with the optimized thickness was studied. The thickness of clamp was set from 8 mm to 11 mm, the respective von-misses stress against load from 100 N to 500 N were studied as shown in Fig. 12. Maximum von-Mises stress was studied instead of the total displacement, due to the negligible value obtained for the total displacement, hence, maximum von-Mises stress is able to provide more clearer comparison of the effects between different thickness. Loads were applied on the surface of clamp, as the condition contributed smaller safety factor when compared to the force applied at the end surface of clamp, which had indicated a more critical condition. Graph of loads against the thickness varied were plotted for better illustration purpose.

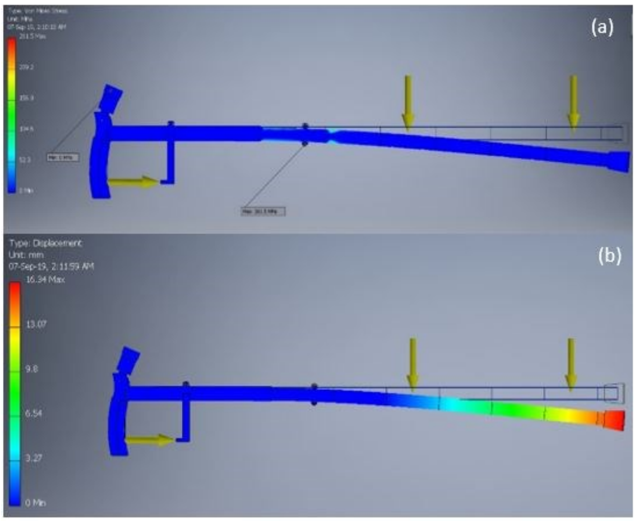

Fig. 12. (a) Von-Mises stress and (b) total deformation of deformation analysis for beam using Autodesk Inventor Professional 2019.

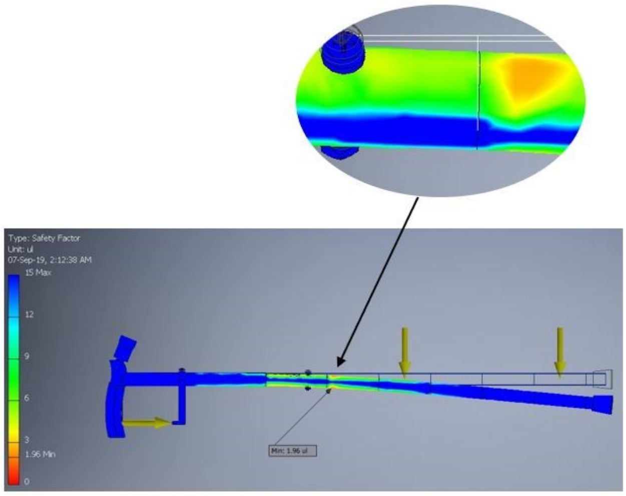

Fig. 14. Safety factor of deformation analysis for beam using Autodesk Inventor Professional 2019.

III. RESULTS AND DISCUSSION

A. Simulation

The outcome of simulation for deformation analysis for the entire walking cane was as shown in Table IV. The maximum von-Mises stress for the beam is 261.5 MPa, and displacement of 16.34 mm as shown in Fig. 13. The minimum safety factor occurred at the connection part between two different diameters of cylindrical rods, which is 1.96 as indicated in Fig. 14. The occurrence of low value in safety factor might due to the shortage of simulation system in identifying the merging connection between two rods.

Table IV. Simulation Results of Beam Analysis.

Simulation Task	Minimum value	Maximum value
Von-Mises stress (MPa)	0	261.50
Total deformation (mm)	0	16.34
Safety factor	1.96	15.00

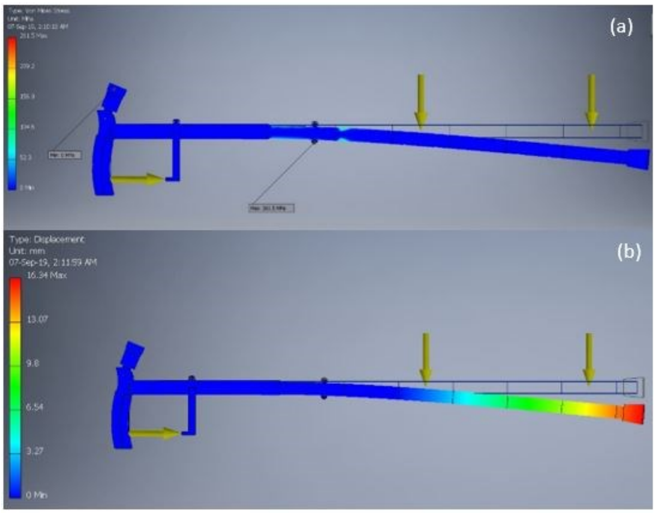

Fig. 13. (a) Von-Mises stress (max = 261.5 MPa) and (b) total deformation of deformation (max =16.34 mm) analysis for beam using Autodesk Inventor Professional 2019.

However, the safety factor can be increased by strengthen the connection between two rods, such as by welding.

The hybrid walking cane was simulated as a fixed end column when it was applied as walking cane. The hybrid walking cane was expected to withstand 800N of user's weight. The maximum von-Mises stress simulated is 209.9 MPa while the total displacement expected to occurred is 5.215 mm as shown in Fig. 15. The outcome of simulation was as shown in Table V. Minimum safety factor of column presence between hand grip and clamp with the value of 3.08.

Table V. Simulation Result of Buckling Load Analysis for Column Using Autodesk Inventor Professional 2019.

Simulation Task	Minimum value	Maximum value
Von-Mises stress (MPa)	0	209.90
Total deformation (mm)	0	5.22
Safety factor	3.08	15.00

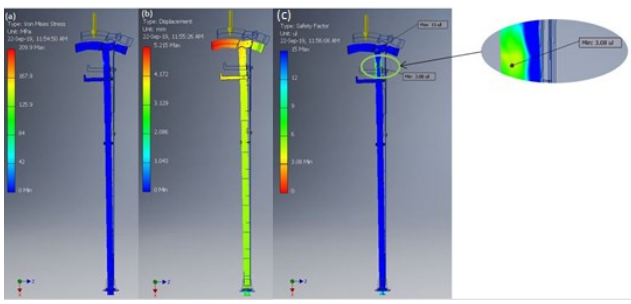

Fig. 15. (a) Von-Mises stress (max = 209.9 MPa), (b) total deformation (max = 5.22 mm) and (c) safety factor (min = 3.08) of buckling load analysis for column using Autodesk Inventor Professional 2019.

The simulation of clamp was created based on the resultant force computed, which is 373.1 N, as well as two different positions of force applied. The force was applied on the surface of clamp where it contacted with the handrails for the first simulation, while the force is expected to have reaction force from its opposite for second simulation. The outcomes of simulation with resultant force of 373.10 N applied on the surface contact of clamp with handrail is shown in Fig. 16 and summarized in Table VI. The maximum Von-mises stress is 26.10 MPa while the maximum displacement is 0.06 mm as shown. The safety factor of the clamp had achieved 3.17 which is considered to be safe for human usage application.

Table VI. Simulation Results for Clamp Using ANSYS 19.0 with Resultant Force of 373.1 N Applied on Clamp's Surface.

Simulation Task	Minimum value	Maximum value
Von-Mises stress (MPa)	0	26.10
Total deformation (mm)	0	0.06
Safety factor	3.17	15.00

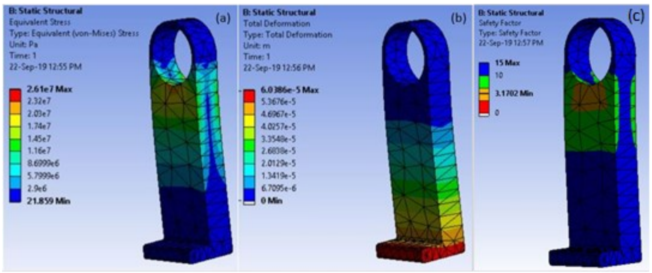

Fig. 16. (a) Von-Mises stress, (b) total deformation and (c) safety factor of deformation analysis for clamp using ANSYS 19.0 by applying the resultant force of 373.1 N.

The outcomes of simulation with resultant force of 373.10 N applied on the end surface of clamp and its reaction force at the opposite was shown in Fig. 17 and summarized in Table VII. The maximum Von-mises stress was 17.57 MPa, relatively smaller when compared to previous case, while the maximum displacement was 0.03 mm. The clamp with possible twisted condition has factor of safety with value 4.71.

Table VII. Simulation Results for Clamp with Reaction Force Occurred at The End Surface of Clamp Using ANSYS 19.0.

Simulation Task	Minimum value	Maximum value
Von-Mises stress (MPa)	0	17.57
Total deformation (mm)	0	0.03
Safety factor	4.71	15.00

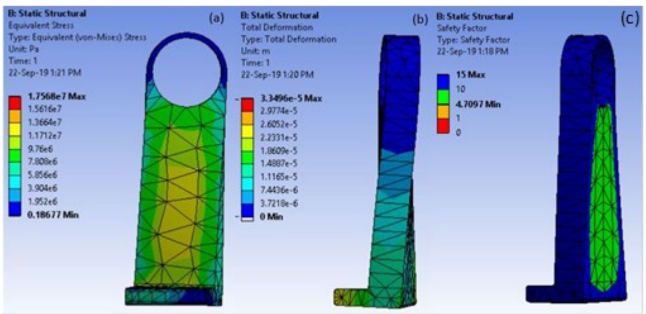

Fig. 17. (a) Von-Mises stress, (b) total deformation and (c) safety factor of deformation analysis for clamp using ANSYS 19.0.

The line graphs as shown in Fig. 18 indicated the relationship between the variation of load that greater or smaller than resultant force computed and their respective Von-mises stress and displacement. It is clear to see that the clamp had reached its elasticity limit when greater load than resultant force was applied and the transition of trend between 400 N and 500 N presence with negligible manners, which the slope did not change significantly. The graphs for both conditions shared same patterns, where the change become negligible once the elastic limit of clamp was achieved.

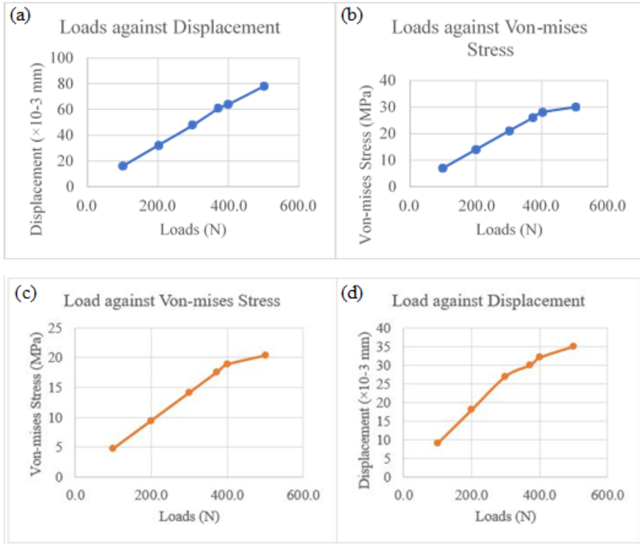

Fig. 18. Graphs of (a) loads against Von-Mises stress and (b) loads against displacement for force variation applied on clamp's surface, and (c) loads against Von-Mises stress and (d) loads against displacement for force occurred at the end surface.

B. Design Optimization

Design optimization was conducted on the clamp part with respect to different thickness. The thickness set was 10mm for the prototype fabricated, nonetheless, different thickness was executed in simulation to study the possibility in design optimization. By observing Fig. 19, the highest thickness of 11 mm contributed to the lowest maximum von-Mises stress, while the smallest thickness of 8 mm contributed to the highest value of von-mises stress.

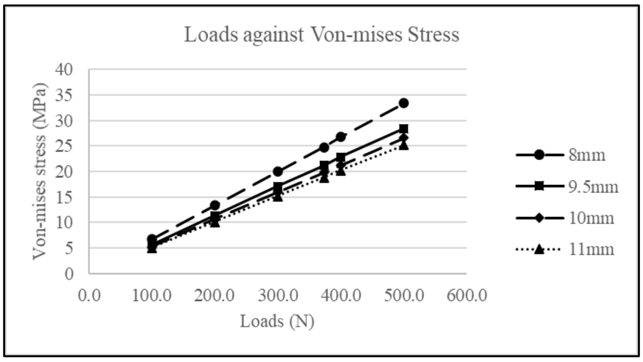

Fig. 19. Graph of different loads varies from 100 N to 600 N against their respective Von-mises stress.

The optimization in the design occurred when there is reduction in mass, while achieving constant maximum von-mises stress. By observing the result obtained, the thickness of 8 mm contributed to the maximum von-mises stress of 33 MPa, which had exceeded the von-mises stress resulted from resultant force 373.1 N with the value of 20 MPa by 65 %. Hence, the thickness was not encouraged to be reduce to 8 mm. The difference of 9.5 mm and 10 mm was too small, which might lead to less significant result for reduction made. Despite the low value in von-mises stress implied by thickness

11 mm, the results for both 11 mm and 10 mm were closed as shown in Fig. 19, aside of increment in the mass of product, the increment in thickness was not necessary. Thus, 10 mm in thickness serves as the ideal thickness for the product design.

IV. Conclusion

The conceptual design and analysis of a staircase climbing aid, also known as the hybrid walking cane were depicted in this work. Aluminium alloys were selected as the ideal materials for hybrid staircase walking cane construction. The simulation results of the design show that the maximum allowable force applied are 80 kilograms (784.8 N) and 100 kilograms (981 N) for a human weight, when the hybrid walking cane is used as a *staircase climbing aid* and a *walking aid* respectively. The staircase climbing aid designed and developed in taking the mobility and safety factor of product into main consideration. However, the developed prototype only limited to usage on handrail with flat surface, which its width stated between 7 cm to 7.5 cm, instead of handrails with curve surface and width greater than 7.5 cm.

There are a few studies worth carrying out for the future developments, concerns of the improvement in functionality and users' experience.

The current work had been mainly focusing on the mechanism of the hybrid staircase climbing aid, leaving the study of ergonomics outside the scope of research. The materials of handgrip could be changed: instead of purchase existing hand grip from market, the gripping force shall be studies based on different materials, in order to increase the friction force between hand palm of users and the handgrip.

Besides, bending flexural test could be conducted on the actual prototype to further investigate on its practicability of the design, in order to verify the outcome of product analysis carried out using theoretical and numerical simulation.

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