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THE IMPLICATION OF HUMAN CENTROID VARIATION DUE TO THE BENDING OVER OF A HUMAN BODY

Timothy Kwan-fai Chan*, XiaoYing Lu, Alpha Chi Him Tsang
Department of Construction, Environment and Engineering, Technological and Higher Education Institute of Hong Kong, Hong Kong region, China.
Corresponding Author: Timothy Kwan-fai Chan

Abstract: Work at height is one of the construction activities, and a drying rack is one of the construction products that may need to be considered in the context of construction safety. Both of them involve people standing in a posture with inclining or bending their body out from a stable and safe point toward a place in the air. Conventionally, the construction industry concerns the height of the barrier, the parapet, and the window frame. However, people falling from height can happen when the centroid of the people moves out from the stable point due to the posture of inclining or bending. The study investigates the relationship between the inclining and bending posture of the human body with the variation of centroids and suggests a reference for the inclining and bending limit for designing the gap between the platform and the wall for scaffolding and the size of a drying rack. The reference supporting loadings required for the guard-rail design of scaffolding and the cantilever support design of drying racks are also suggested.
Keywords: Safety; Drying rack; Scaffolding; Height restriction of protection barrier; Work at height

1 INTRODUCTION

As falling from a height is one of the critical safety concerns that the construction industry shall account for in their design for permanent features or construction operations, the variation of the centroid or the line of action of a human body may be a critical reference for the industrial practice. Beyond the accidents of construction workers working on scaffolds, there are occasional accidents of falling from height while using drying racks in Tsing Yi Island, Hong Kong region. The accidents raise concerns not only about the practice of the public in using drying racks, but also the out-of-reach requirement in designing the drying racks. The research is similar to the out-of-reach requirement research [1], but this research focuses more on the variation of the human body centroid with the bending over of the human body. The study aims to find out the relationship between bending over a human body and the variation of the centroid of a human body, and to provide reference data for reviewing the drying racks' design. Accompanied by two final-year project students, the research is mainly carried out from January to August 2025 in Hong Kong region.

The out-of-reach requirement research by Sanders & McCormick mainly concerns the requirement of a barrier height [1]. In Hong Kong region, the figure "1.1m" as the minimum height requirement for the protection barrier appears on the PNAP APP-110, Clause 2 [2], and the repealed Cap. 123B, s8(2)(b) [3]. The new Building (Construction) Regulation, Cap. 123Q [4], does not mention this. The standard number 1910.29(b)(1) of OSHA defines that the height of top rails should be 42 inches (107 cm) [5], which matches the figure used in Hong Kong region. But there is no experimental data to support this figure. The guidelines for scaffolding also concern only the height of guard-rail [6,7]. For the space between the platform and the wall, the guideline states that it 'should be as small as practicable' (Labour Department, 2024, p.26, clause 5.3.1 (k); Labour Department, 2013, p.28, clause 5.1.4 (k)) [6,7]. Therefore, there is no reference for the bending over limit while working on a scaffold. However, the focus on the height of the barrier may not be sufficient, as a human body would not fall at height if one's body centroid has not passed by the edge of the floor due to the inclining or bending over of the body.

For research on work at height, Xin et al. carried out a human reliability assessment [8]. Mohammad et al. applies drones and deep learning for safety monitoring [27]. Ibrahim also applies a deep learning-based system to predict work at height behavior [10]. Rubio-Romero, Rubio, and García-Hernández concerns with equipment safety for work at height [11]. Kissiková, Lenka and Dlugoš tries to obtain data from testing ropes [12], carbines, and other accessories for improving safety equipment for the good of Czech's construction industry. Jabbari, Sadeghi, and Sepehr reviews the ergonomic design of safety harnesses to make them comfortable to encourage workers to use this personal protective equipment [13]. The recent trend of research on work at height may concentrate on the application of digital and robotic technology and safety equipment design. The Hong Kong Institution of Engineers is also concerned about the safety of work at height. The Hong Kong Engineer journal publishes many articles about the safety of work at height. But, they may be concerning the structural capacity of scaffolds [14]; the safety management [15,16]; and a modular scaffolding system [17]. It seems that the study of the variation of the centroid of a human body is not the main trend of research for work at height.

The research on drying rack design is also trending towards applying digital technology. For example, adopt a central controller and multiple sensors for the decision-making of a drying rack system [18]; concerning the convenience and digitising the home life by applying the Internet of Things [19]. Ying-Hsiang, Yin-Ching & Chia-Pao concerns that the accident may happen to the elderly while rushing to collect clothes from outside a building before it rains [20]. The research applies an invention system for problem-solving. It is not a research to particularly investigate the relationship between bending over the body and the variation of the human centroid.

It seems that the study related to the human centroid with one's inclining or bending over posture may not be a hot topic. There is no measuring equipment available for this particular study. In measuring the human centroid in this study, the segmentational method may not be adopted [21,22]. The best way may be to adopt the reaction board method. This method involves a person holding a certain body position while measurements are taken using a rigid board with special feet and a scale (2D) or scales (3D) to measure the ground reaction force under the feet of the board [23]. This method is proven to be more valid than the suspension method [24].

Beyond direct measuring of the overall centroid of a human being, the application of anthropometry can be another way to benefit construction practice. Anthropometry studies of working men have been used for safe and convenient workplace design [25], to reduce drudgery and enhance safety by farm equipment design for female workers and to reduce the risk of back pain due to manual material handling [26,27]. The generation of a mass distribution anthropometrical spectrum of the practitioners may be an improvement in the design and practice in the construction industry. Though the research on the human centroid variation topic in the fields of mechanics and ergonomics, it can form multidimensional connections with the core goals of the Greater Bay Area's sustainable development, namely high - quality economic development, environmental friendliness and social inclusiveness, through the transmission path of "basic scientific research → technological innovation → industrial application → regional development".

2 METHODOLOGY

Unless the distribution of mass of a human being is known, the best way to investigate the relationship between the variation of the human centroid and the bending over posture of a body is through empirical experiments. The experiments would involve the measurement of several human subjects by newly created equipment. The human subjects who participated would be arranged to stand on the newly created equipment, which is supported by three load cells. The readings of each load cell would be taken individually. The distances of each load cell to a reference point would also be taken. By application of the fundamental theory of centroid calculation, the centroid of the body can be calculated. While the human body bends forward, the centroid of the body will move forward. The change of the centroid will be reflected in the change of readings in the load cells. By application of the fundamental theory of centroid calculation again, the relationship between the variation of the centroid with the bending over posture of the body can be figured out.

Particularly, the objective of this study is to produce data and insight for drying rack practice and design. The centroid of the human subjects would be measured in three stages. In the first stage, the subjects are allowed to stand on the measuring equipment and move forward while stretching their right arm. In the second stage, the subjects are required to put their left hand on a reference beam that is close to them, as a simulation of putting a hand on the frame of a window, and carry out the same movement as in the first stage. In the third stage, the subjects are required to put their hand on the far edge of the protection frame, as a simulation of putting a hand on a drying rack, and carry out the same movement as in the first stage. The change of the centroid of the subjects would be calculated from the change in readings of the three load cells.

It is the concern of this study to improve safety in using drying racks. The study is interesting in that it finds out how much a body can move out so that the centroid of the body is still located within the mid-third of the footprint, the edge of the footprint, and the edge of the window. The loading for the drying rack design will be suggested.

2.1 The Equipment

The measuring equipment is composed of an aluminum triangular frame resting on three plastic supports. A plastic survey plate is stuck on a timber board, which is attached above the aluminum frame (Figure 1).

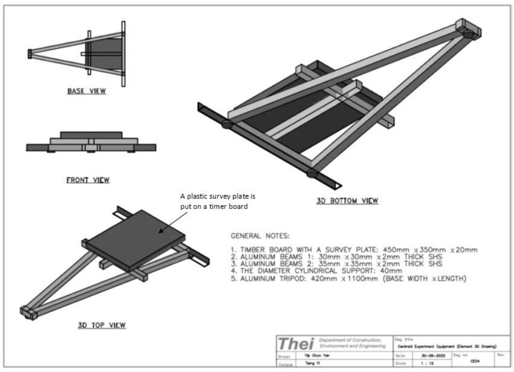


Figure 1 The Measuring Equipment

A plastic survey plate is used for measuring the footprint of the subjects. The weight of the subjects who are standing on the plastic survey plate will transfer to the timber board below, and further to the aluminum frame and the three plastic supports, and finally to the three load cells.

Figure 2 presents the arrangement of the measuring equipment:

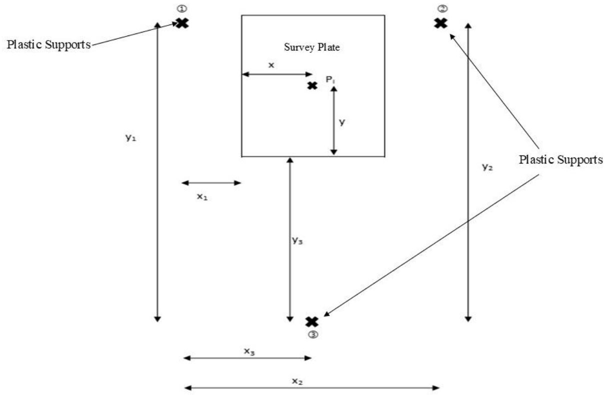


Figure 2 The Arrangement of the Measuring Equipment

The reference of the centroid of the human bodies refers to the left and bottom axes of the survey plate. The measured subject centroid is denoted as x and y. x_1, x_2, x_3, y_1, y_2 and y_3 are the distances measured from the survey plate to the plastic supports. As measured, the values of these distances are listed in Table 1:

Table 1 Measured Object Centroid from Survey Plate to Plastic Support

Item	Distance (mm)
x_1	78.45
x_2	448.87
x_3	217.85
y_1	1054.1
y_2	1051.2
y_3	662.57

The main structure of the measuring equipment comprises the timber board and the aluminum frame, which is considered sufficient to take up a human being with a weight of 100 kg while minimising the loading of the equipment. The plastic supports provide the contact points with the load cells. It can be assumed that the load to be measured is at a point. Plastic is used to ensure good contact with the load cells. The measurement is done using three points to ensure effective transfer and distribution of the load under a stable pattern.

The load cells used in this experiment are three platform scales. Two of the scales can read to 10 g. The sensitivity of reading in 10 g is that it can read a piece of 200 mm×200 mm of human flesh with a 1 mm movement ($\sqrt{(4\times10)/0.001}=200$).

A timber frame is erected for access and protection of the subjects who participated in the experiment. The timber protection frame is composed of a stepping platform and a pair of guard rail frames braced by a lintel beam (Figures 3 & 4). The subjects would step on the stepping platform after taking off their shoes, and step on the survey plate of the measuring equipment safely. The guarding rails on both sides of the subject act as a protective precaution.

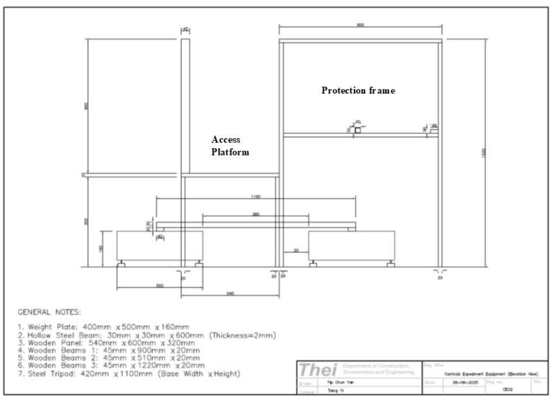


Figure 3 The Elevation of the Timber Protection Frame

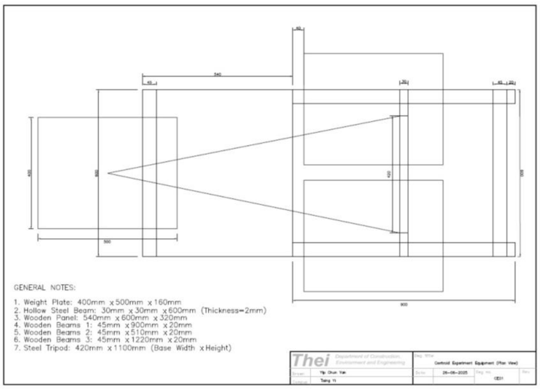
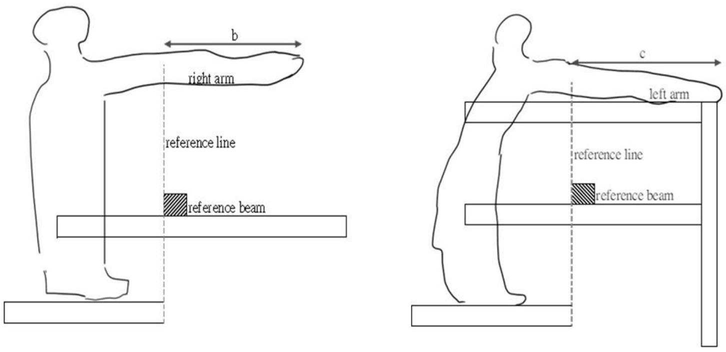


Figure 4 The Plan View of the Timber Protection Frame

The timer protection frame has another function to act as a reference system for measuring the bending over displacement of the body. There are two rails for each face of the guard rail frames, the upper one and the lower one. A 30 mm×30 mm aluminum beam rested on two aluminum plates that were secured across the guard rail frames. The aluminum beam is used as a reference beam for measuring the displacement of the body and is named as "reference beam". The reference beam is adjusted to align its inner face to the edge of the survey plate with the help of a pair of strings stretched by Japanese 5-yen coins balanced by old keys (Figure 5). Therefore, the inner face of the reference beam is set as the reference line of the displacement of a body and denoted as zero displacement. A ruler with the end starting from zero reading is fixed with the reference beam. The bending over displacement can be measured from the ruler's reading.

The timer protection frame is also used as a holding frame for simulating actual practice in using a drying rack. The subjects put their left hand on the reference beam as if they were putting their hand on the frame of a window. The subjects put their left hand on the far corner of the top rail of the left guard rail frame as if they were putting their hand on the draying rack (Figure 5). Thus, an aluminum beam resting on two aluminum plates is adopted to take the extra bending moment on the reference beam and the punching shearing force of the lower rails. While Figure 6 presents the completed setup:



(a) (b)

Figure 5 (a)The Subject Pushes One's Hand against the Frame; (b)Simulating Putting One's Hand on a Window Frame or Drying Rack

Figure 6 The Completed Setup of Measurement

2.2 Theory

The fundamental theory of centroid calculation is adopted for this experiment. The centroid of mass of a human body is calculated by:

$$\overline{x}=\frac{\sum_i^n p_i x_i}{\sum_i^n p_i} \tag{1}$$

Where: $\overline{x}$ is the centroid of the body from the reference point.

p_i is the weight measured by the individual load cell.

x_i is the distance of the individual load cell from the reference point.

In the application of this study, the equations are further developed as follows:

Let P_i is the additional force due to body weight

Let P_{1i} is the additional force on point 1 due to body weight

Let F_{10} is the original force on point 1 due to the self-weight of the measuring equipment

Let F_{1i} is the total force on point 1 measured by load cell 1

$$P_i=P_{1i}+P_{2i}+P_{3i} \tag{2}$$

$$P_i(y+y_3)=P_{1i}y_1+P_{2i}y_2$$

$$y=\frac{P_{1i}}{p_i}y_1+\frac{P_{2i}}{P_i}y_2\text{-}y_3$$

$$P_i(x+x_1)=P_{3i}x_3+P_{2i}x_2$$

$$x=\frac{P_{3i}}{p_i}x_3+\frac{P_{2i}}{P_i}x_2\text{-}x_1 \tag{3}$$

Concerning the stability of the human body under this study, the concept of the mid-third test is borrowed. The mid-third test is widely adopted in stability checking in pad footing foundation design in Civil Engineering. There will be no titling, and the foundation can be effectively used while the line of action of the loadings acting on the footing is located within the mid-third of the footprint. The footprint is defined by the farthest edge, which is subject to rotations on the footing. For controlling the experiment, the footprints of the subjects are regulated by restricting their feet in a rectangular frame (Figure 7). Detailed procedure should refer to supplementary information.

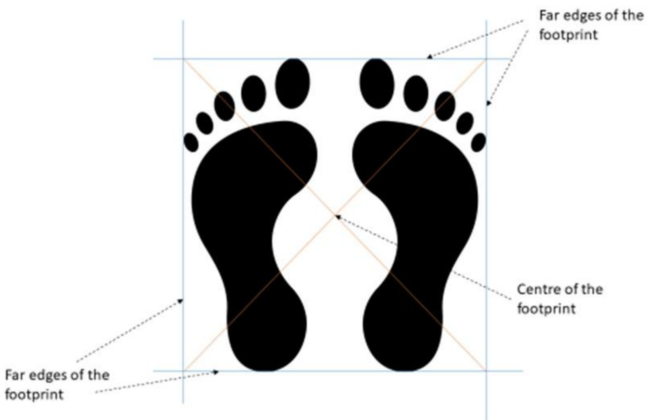


Figure 7 The Footprint of a Subject

3 DETAILED PROCEDURE OF THE MID-THIRD TEST

1. Set up the three scales on the same level with two spirit levelling rulers in both directions. The three scales are each to be set up at the same level.
2. Put the centroid measuring equipment on the three scales and ensure it is level in both directions.
3. Set up the access platform and protection frame. The length from the edge of the reference beam (reference line) to the far corner of the protection frame "c" would be measured (Figure 5b).
4. Set up three cameras to take the readings of the three scales and one camera to take the variation of the feet.
5. Measure the body height "a" of each subject and assign a subject code.
6. Take the initial reading "F_{i0}" of the three scales due to the self-weight of the centroid measuring equipment before the experiment for each subject.
7. Allows the subject to step on the centroid measuring equipment. (For the sake of safety, the subject is suggested to take off one's shoe and step on the access platform before stepping on the survey plate of the centroid measuring equipment.)
8. Take the reading of the four edges of the footprint on the survey plate.
9. Switch on the cameras to take the readings "F_{ii}" of the three scales and the variation of the feet continuously until the end of the experiment session.
10. As a part of another experiment, the reading for evaluating the standing stability of the subject would be taken first.

(The detail refers to that experiment.)

11. Requires the subject to stand with the backbone straight. Request the subject to stretch out the subject's right arm and measure the stretched length of the arm from the reference line to the tip of the hand "b" (Figure 5a).
12. Wrap a red string on the right arm of the subject while keeping the backbone straight with two old keys to stress the string. The string starts at point zero at the inner edge of the reference beam.
13. Allow the subject to move the subject's body, the researcher shouts out the reading along the reference ruler while the string clinging to the subject's hand reaches certain particular marks, such as 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm, 40 cm, and 45 cm.
14. The subject is allowed to stand straight again and put the subject's left hand on the reference beam and repeat step 13.
15. The subject is allowed to stand straight again and put the subject's left hand on the far corner of the protection frame and repeat step 13.
16. After the researcher shouts out "the end of the session", the subject is allowed to leave, and the researcher switches off all cameras.
17. From the recording of the camera taking the feet, determine whether to accept the reading. (For example, reading cannot be accepted while the subject moves one's foot from the original footprint.)
18. The variation of forces on the three load cells is taken as the reading of the load cells taken at specific times from the cameras. The specific times are defined by the researcher's shouting during the experiment. It ensures that the readings of the three load cells can be taken at the same time. After deducing the initial readings of the three load cells before the subject steps on the survey plate, these readings are used to calculate the variation of the centroid with the moving postures.
19. Calculate the variation of the centroids of the subject with the bending over postures of the body.

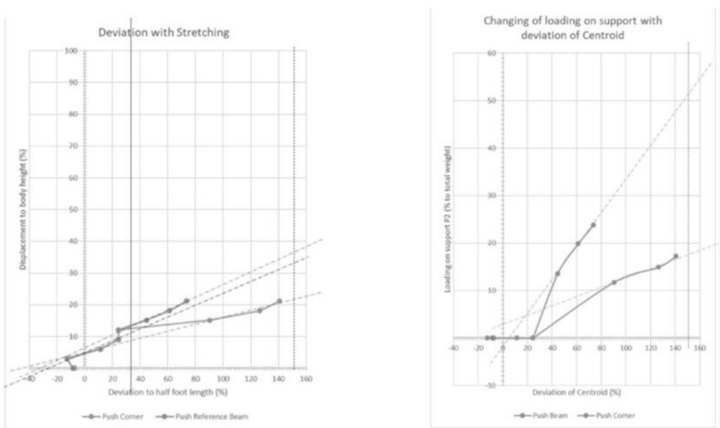
4 RESULTS AND DISCUSSION

From the data obtained, the centroids of each variation of body posture can be calculated by the equation above. The body weight of the subjects would be calculated by averaging the summation of readings of the three load cells in each trial.

The deviation is the centroid's displacement from the footprint's centre. The deviation would be considered by comparing it with half of the footprint to reduce the effect of different people with different foot lengths. The deviation in percentage would be: the deviation/half of the footprint length×100%.

The mid-third margin is defined as the distance between the edge of the mid-third of the footprint and the centroid.

Finally, the chart for the displacement of the body to the percentage of deviation of the centroid from half of the footprint and the chart for additional supporting force to half of the footprint are plotted for each subject (Figure 8). One of the examples is printed below. The percentage of the displacement is: the displacement the body moves/total height of the subject×100%.

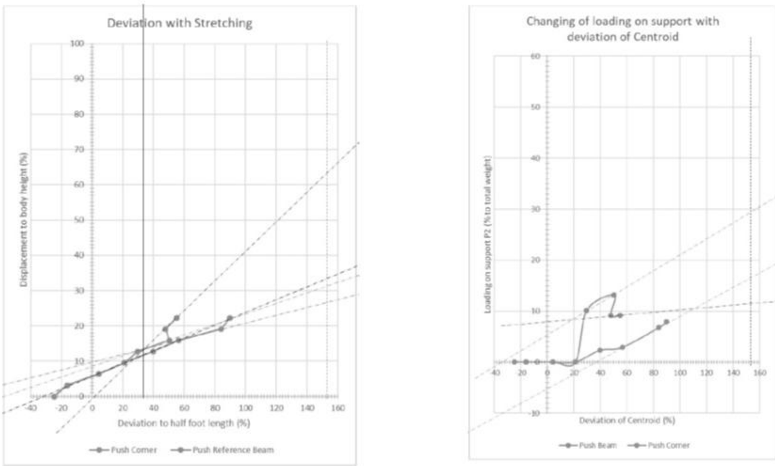


(a) (b)

Figure 8(a)The Chart for the Displacement of the Body on the Percentage of Deviation of the Centroid from Half of the Footprint; (b)The Chart from Additional Supporting Force to Half of the Footprint is Plotted for Each Subject

The first chart of each subject would be studied and find out the percentage of body movement to allow the centroid of the body to reach the mid-third edge, the edge of the footprint, and the inner edge of the reference beam. The second chart of each subject would be studied to find out if additional force needs to be added to the supports when the centroid reaches the footprint edge and the reference beam inner edge. The additional force is in terms of the percentage of the total body weight.

Sometimes, the subject may be too tense and push one's toe hard to the ground. The additional force on the toes will change the line of action of the total forces on the subject. Figure 9 presents the influence of the tense condition of a subject. The consolidated result is put in Appendix A in the supporting information.



(a) (b)

Figure 9(a)The Chart for the Displacement of the Body on the Percentage of Deviation of the Centroid from Half of the Footprint; (b)The Chart from Additional Supporting Force to Half of the Footprint are Plotted for Each Subject (in tense condition)

The first concern of this study is the variation of the centroid with the bending over displacement of a body. With reference to the chart “Deviation of Centroid of the whole body with displacement of a body”, the data of free standing can form a straight line with the data while holding the reference beam, see Figure 10. It is reasonable as holding a reference beam close to one’s body should have the approximate behavior of a free-standing. From that line, it can be observed that the subjects may reach the edge of the mid-third of one’s footprint when one displaces to 10.8% of one’s total height and thus start to be unstable. When the subjects displace to 23.4% of their total height, the centroid of the subjects will fall out of the edge of their footprint. When the subjects displace to less than 33.1% of their total height, their centroid will fall out of the edge of the window.

Figure 10 Align the Reference Beam with the Survey Plate by a Pair of Strings

It can be observed that the required movement of a body to allow the centroid to move away from a reference point is increased when the subject puts one’s hand on the reference beam compared to the free-standing situation. The displacement of the body to one’s total height is increased from 23.4% to 29.2% for reaching the front edge of the footprint and is increased from 33.1% to 40% for reaching the edge of the window. The action of putting the reference beam simulates the practice of holding the frame of a window while stretching the body to collect clothes from a drying rack. On average, a subject can further displace one’s body by (29.2%-23.4%=5.8%; 0.4652 m-0.3705 m=0.0947 m) when reaching the front edge of the footprint; and (40%-33.1%=6.9%; 0.6378 m-0.5231 m=0.1147 m) when reaching the edge of the window frame.

It can also be observed from the summarised data that the required displacement of a body to allow the centroid to move away from a reference point decreases with an increment in the holding distance. With reference to the front edge of the footprint, the percentage of displacement of a body is reduced from 29.2% to 22.2% while the subject holds not the reference beam but the far corner of the protection timber frame. With reference to the window edge, the percentage of displacement of the body is reduced from 40% to 29% while the subject holds not the reference beam but the far corner of the protection frame. The difference between the sets of data is 7% and 11%, respectively. It can be considered the displacement percentage, holding other points, which can be estimated from proportionate data. It indicates that a subject will be much more likely to fall when the subject holds a point on the drying rack. However, it seems that the subject is not falling when put on a point of the drying rack. It is because the drying rack helps to take up part of the weight of the subject. Then, the subject is supported by the subject's feet and the drying rack. However, an accident may happen if the drying rack cannot take up the part of the weight of the subject.
One of the practical concerns is how far a hand can be stretched out when using a drying rack. With reference to the data, the allowable stretch of the hand without passing the critical point is listed in Table 2:

Table 2 Allowable Stretch-out Lengths without Allowing the Centroid of a Body to Pass Critical Points

	Reach the footprint edge	Reach the window edge
Holds reference beam	60.55%	71.42%
Holds the far corner	53.54%	60.37%

The reference length of the stretch out of the hand holding the far corner without allowing the centroid to move away from the window is 958 mm. If the subject is holding the edge of the window, he can further stretch out his hand to 1135 mm. That means: someone stretches out the hand within 958 mm and 1135 mm, the centroid of one does move away from the window, but the one still held by the drying rack structure. However, as one suddenly likes to catch something far from one and move one’s hand from holding the edge of the window to holding a point 500 mm from the edge of the window, one may be at risk of allowing one’s centroid to suddenly move away from the window edge. For example, one may be at risk of the centroid moving away from the window edge while one holds the window edge with one’s hand stretched out to 950 mm, but suddenly moves the hand forward to hold a point far away from one to allow one’s other hand to catch something far away from one. Therefore, the lengths generated are meaningful for defining the maximum allowable references, such as the width or length of a drying rack, the distance allowed between scaffolding and the face of the structure to be reached, the distance kept from a gondola to a building surface and the distance allowed for a worker to receive a hanging facade while the worker stands at the edge of an opening.
Another concern in this study is to find out the reference forces for design. Even though the stretch-out distance can be controlled, the holding support cannot provide the required supporting force, which may lead to the fall of the body. The percentage of weight pushing on the far corner of the protection frame when the centroid reaches the edge of the window is 18%. The percentage of weight on the far corner increases with the distance the centroid moves out. Ultimately, the maximum percentage of weight may be 100%. However, it may be too harsh to require to demand 100% of the weight in design. The designed weight percentage for reference should be defined by the restriction of the centroid moving out. In case the requirement is restricting the centroid from moving out of the window edge, the percentage adopted is 18%. Another approach is to consider the real situation of the site or the incidental condition, to define the percentage from the chart. For example, 18% is considered as the reference; the supporting weight it needs to take is 14.13 kg. In designing a drying rack, it may take up the loading from wet clothing with this additional 14.13 kg. For the operation of receiving façade panels, the handling operation needs to account for this additional 14.13 kg.
Another observation is that the ‘centroid’ of the subject can be pulled back while in a tense condition. In fact, it is not the change of the centroid of the human body, but the change of the line of action of the total forces on the human body due to the additional force on the toe. Through the observation of the experiment, sometimes the subject may be too tense and unintentionally put great force on their toe. This additional force can pull back the line of action and allow much more displacement of the body to reach a reference point. When the subject pushes on the reference beam (window frame), the tense condition allows an increase of displacement by (46.4%-40%=6.4%; 0.7371 m-0.6378 m=0.0993 m) without a fall from the window. When the subject pushes on the far end (a point on the drying rack), the tense condition allows an increase of displacement by (42.7%-29% = 13.7%; 0.6692 m-0.4595 m=0.22097 m) without a fall from the window. Although this discovery can be an insight into manufacturing a shoe that increases the force added by toes, the present situation is that some of the old men used to account for the utmost stretching length, considering also this force by their toes, but lost balance suddenly because they cannot provide this additional force due to ageing or fainting.

5 CONCLUSION

This experiment demonstrates that leaning and pushing against a reference beam provides higher safety levels than maintaining a free-standing posture. The reference beam adopted in this study simulates common architectural and construction components, including window frames, building parapets, and scaffold crossbars. Nevertheless, safety risks arise when participants grip the far end of the protective frame. This posture simulates the real-world working scenario where workers grasp external components beyond their standing coverage, such as the end of a drying rack or protruding structural elements during scaffold operations.

Despite the limitations of a relatively small sample size and a participant pool dominated by housewives, this study serves as a preliminary exploration of safety issues related to forward bending movements near building openings, which differs from conventional research focusing on height restriction management. The findings provide fundamental references for the structural design of exterior drying racks and on-site construction safety optimisation. The front-edge boundary of the effective standing footprint is identified as a critical safety indicator. The maximum safe outreaching length of the human arm is determined as 46.23% of total body height, equivalent to 0.7628 m, which represents the minimum critical force data measured when hands push against the far end of the protective frame. Accordingly, the clearance between scaffolds or suspended gondolas and external walls is recommended to be designed within 750 mm.

In terms of structural load design, window frames, parapets, as well as crossbars of scaffolds and gondolas, should be capable of bearing a force equivalent to 44.5% of the human total body weight (34.9 kg), which is the maximum load recorded when pushing steadily against the reference beam. For the support structure design of exterior drying racks and safety assessment of grasping external wall structural components, the structural bearing capacity should meet a load requirement of 18% of total body weight (14.13 kg), corresponding to the maximum force generated when gripping the far end of the protective frame.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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REFERENCE

[1] Sanders M S, McCormick E J. Chapter 13: Applied anthropometry, work-space design, and seating. Human Factors in Engineering and Design (7th Edition), New York: McGraw-Hill, 1993: 429-430.

[2] HO Chun-hung. PNAP APP-110 – Protective Barriers. Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers. Hong Kong: The Buildings Department, 2026. https://www.bd.gov.hk/doc/en/resources/codes-and-references/practice-notes-and-circular-letters/pnap/APP/APP110.pdf.

[3] Department of Justice. Cap.123B Building (Construction) Regulations. Hong Kong Legislation. Hong Kong: The Government of HKSAR, 2012: 1-78. https://www.elegislation.gov.hk/hk/cap123B@2012-02-09T00:00:00.

[4] Department of Justice. Cap.123Q Building (Construction) Regulations. Hong Kong Legislation. Hong Kong: The Government of HKSAR, 2021: 1-66. https://www.elegislation.gov.hk/hk/cap123Q.

[5] OSHA. "1910.29". Fall protection systems and falling object protection – criteria and practices. Occupational Safety and Health Administration, Ed. Washington, DC, USA: U.S. Department of Labor, 2019: 1910. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.29.

[6] Labour Department. Code of Practice for Metal Scaffolding Safety (Second Edition). Hong Kong: The Government of HKSAR, 2013: 1-98.

[7] Labour Department. Code of Practice for Bamboo Scaffolding Safety (Fifth Edition). Hong Kong: The Government of HKSAR, 2024: 1-120.

[8] Li X, Guo Y, Ge F L, et al. Human reliability assessment on building construction work at height: The case of scaffolding work. Safety Science, 2023, 159: 106021.

[9] Shanti M Z, Cho C S, de Soto B G, et al. Real-time monitoring of work-at-height safety hazards in construction sites using drones and deep learning. Journal of Safety Research, 2022, 83: 364-370.

[10] Karatas I. Deep learning-based system for prediction of work at height in construction site. Heliyon, 2025, 11: e41881.

[11] Rubio-Romero J C, Rubio M, García-Hernández C. Analysis of construction equipment safety in temporary work at height. Journal of Construction Engineering and Management, 2013, 139: 9-14.

[12] Kissiková L, Dlugoš I. Comprehensive evaluation of the work at height. Acta Metallurgica Slovaca, 2018, 24: 100 -106.

[13] Jabbari M, Sadeghi Naeini H, Sepehr P. A Systematic Review of The Design of Safety Harnesses for Work at Height and The Effects of Suspension During a Fall. Journal of Health and Safety at Work, 2024, 14: 880-902.

[14] Tong T, Wang O. We need industry breakthrough of Truss-out Scaffold and critical temporary work system. Hong Kong Engineer, 2024, 52(3): 20.

[15] Tse V W F. Floor openings protection on construction site. Hong Kong Engineer, 2023, 51(9): 17.

[16] Tse V W F. Critical points on inspection, examination and testing of lifting appliances and gear. Hong Kong Engineer, 2024, 52(7): 13.

[17] Au G W Y. The development and prospect of metal scaffold. Hong Kong Engineer, 2023, 51(1): 20.

[18] Zhang S, Hu W, Liang W, et al. An efficient intelligent control algorithm for drying rack system. IET Communications, 2023, 17: 1691-1705.
[19] Xing X, Zhang C, Gu J, et al. Intelligent drying rack system based on internet of things. Journal of Physics: Conference Series, 2021, 1887: 012002.
[20] Lin Y H, Lee Y C, Chang C P. Establishing an intelligent laundry drying rack using system innovation theory. IOP Conference Series: Earth and Environmental Science, 2020, 603: 012047.
[21] Chebel E, Tunc B. Deep neural network approach for estimating the three-dimensional human center of mass using joint angles. Journal of Biomechanics, 2021, 126: 110648.
[22] Erdmann W. Center of mass of the human body helps in analysis of balance and movement. MOJ Applied Bionics and Biomechanics, 2018, 2: 144-148.
[23] Barnard Health Care Center Of Gravity. 2024. https://www.barnardhealth.us/qualitative-analysis/center-of-gravity.html.
[24] Sharma R, Sharma P, Shaw D. Assessing validity of the reaction board method with suspension method to determine center of gravity. International Journal of Sports Health and Physical Education, 2023, 5(1): 56-59.
[25] Abdalla A, Mohamed A, Abdullah A, et al. Anthropometry of Saudi Arabian male workers. Proceedings of the International Conference on Industrial Engineering & Operations Management, 2018: 2358-2364.
[26] Potdar R, Agrawal K N, Shukla P, et al. Anthropometry of female agricultural workers of Madhya Pradesh. Bhartiya Krishi Anusandhan Patrika, 2021, 36: 1-11.
[27] Ahmad S, Mohammad M. Effect of Anthropometry on Maximum Acceptable Weight of Lift. Proceedings of the International Conference on Industrial Engineering & Operations Management, 2022: 620-626.

APPENDIX

Appendix Table 1 Consolidated Result

No.	Item			Average	Standard Deviation	Maximum	Minimum	Sample no.
1	Distance from the window frame to the far point of the drying rack			0.5515m	0.035428m	0.6m	0.583m	52
2	% of (1) refers to the subject height			35.031%	2.268%	37.975%	32.753%	52
3	Free Standing		% of stretching out allows the human centroid to reach the mid-third of the footprint	10.816%	3.1359%	18.5%	6%	43
4	Free Standing		Distance of stretching out allows the human centroid to reach the mid-third of the footprint	0.1718m	0.054584	0.3293m	0.0972m	43
5	Free Standing		% of stretching out allows the human centroid to reach the footprint toe edge	23.357%	5.2033%	34%	15%	42
6	Free Standing		Distance of stretching out allows the human centroid to reach the footprint toe edge	0.3705m	0.091002	0.6052m	0.243m	42
7	Free Standing		% of stretching out allows the human centroid to reach the window frame	33.124%	8.2025%	41%	19%	42
8	Free Standing		Distance of stretching out allows the human centroid to reach the window frame	0.5231m	0.12909	0.7298m	0.3078m	42
9	Push the window frame	Relax	% of stretching out allows the human centroid to reach the footprint toe edge	29.161%	8.2691%	63%	23.5%	31
10	Push the window frame	Relax	Distance of stretching out allows the human centroid to reach the footprint toe edge	0.4652m	0.156365	1.1151m	0.3995m	31
11	Push the window frame	Relax	% of stretching out allows the human centroid to reach the window frame	40.032%	12.116%	85%	29%	31
12	Push the window frame	Relax	Distance of stretching out allows the human centroid to reach the window frame	0.6378m	0.219822	1.5045m	0.493m	31
13	Push the window frame	Tense	% of stretching out allows the human centroid to reach the footprint toe edge	36.227%	9.0287%	24.5%	24.5%	11
14	Push the window frame	Tense	Distance of stretching out allows the human centroid to reach the footprint toe edge	0.5767m	0.14324	0.4361m	0.4361m	11
15	Push the window frame	Tense	% of stretching out allows the human centroid to reach the window frame	46.364%	11.987%	26%	26%	11
16	Push the window frame	Tense	Distance of stretching out allows the human centroid to reach the window frame	0.7371m	0.189496	0.4628m	0.4628m	11
17	Push on the drying rack	Relax	% of stretching out allows the human centroid to reach the footprint toe edge	22.204%	5.6038%	30.05%	13.5%	25
18	Push on the drying rack	Relax	Distance of stretching out allows the	0.3527m	0.09178	0.4748m	0.2228m	25

No.	Item			Average	Standard Deviation	Maximum	Minimum	Sample no.
			human centroid to reach the footprint toe edge					
19	Push on the drying rack	Relax	% of stretching out allows the human centroid to reach the window frame	29.04%	8.2788%	41%	19%	25
20	Push on the drying rack	Relax	Distance of stretching out allows the human centroid to reach the window frame	0.4595m	0.126419	0.6478m	0.3078m	25
21	Push on the drying rack	Tense	% of stretching out allows the human centroid to reach the footprint toe edge	29.844%	6.2643%	30%	30%	16
22	Push on the drying rack	Tense	Distance of stretching out allows the human centroid to reach the footprint toe edge	0.4702m	0.104107	0.534m	0.534m	16
23	Push on the drying rack	Tense	% of stretching out allows the human centroid to reach the window frame	42.656%	12.418%	35%	35%	16
24	Push on the drying rack	Tense	Distance of stretching out allows the human centroid to reach the window frame	0.6692m	0.187302	0.623m	0.623m	16
25	Free Standing		Stretch out of hand refers to the subject height (%) allows the human centroid to reach the mid-third of the footprint	42.22%	4.56%	51.26%	39.33%	43
26	Free Standing		Stretch out of hand refers to the subject height (m) allows the human centroid to reach the mid-third of the footprint	0.669m	0.089346	0.8963m	0.6372m	43
27	Free Standing		Stretch out of hand refers to the subject height (%) allows the human centroid to reach the footprint toe edge	54.84%	6.31%	66.76%	48.33%	42
28	Free Standing		Stretch out of hand refers to the subject height (m) allows the human centroid to reach the footprint toe edge	0.8689m	0.121719	1.1722m	0.776m	42
29	Free Standing		Stretch out of hand refers to the subject height (%) allows the human centroid to reach the window frame	64.61%	8.28%	72.85%	52.33%	42
30	Free Standing		Stretch out of hand refers to the subject height (m) allows the human centroid to reach the window frame	1.0214m	0.13708	1.2968m	0.8478m	42
31	Push the window frame	Relax	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the footprint toe edge	60.55%	9.24%	98.59%	56.44%	31
32	Push the window frame	Relax	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the footprint toe edge	0.9626m	0.191286	1.7451m	0.9525m	31
33	Push the window frame	Relax	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the window frame	71.42%	12.78%	120.59%	61.94%	31
34	Push the window frame	Relax	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the window frame	1.1352m	0.248823	2.1345m	1.053m	31
35	Push the window frame	Tense	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the footprint toe edge	60.55%	9.24%	98.59%	56.44%	31
36	Push the window frame	Tense	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the footprint toe edge	1.0678m	0.142888	1.0031m	1.0031m	11
37	Push the window frame	Tense	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the window frame	77.13%	11.50%	57.85%	57.85%	11
38	Push the window frame	Tense	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the window frame	1.2282m	0.178495	1.0298m	1.0298m	11
39	Push on the drying rack	Relax	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the footprint toe edge	53.54%	5.53%	59.16%	46.23%	25
40	Push on the drying rack	Relax	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the footprint toe edge	0.8507m	0.108012	1.0298m	0.7628m	25
41	Push on the drying rack	Relax	Stretch out of hand refers to the	60.37%	7.06%	70.11%	52.33%	25

No.	Item			Average	Standard Deviation	Maximum	Minimum	Sample no.
			subject height (%) allows the human centroid to reach the window frame					
42	Push on the drying rack	Relax	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the window frame	0.9575m	0.115755	1.1078m	0.8478m	25
43	Push on the drying rack	Tense	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the footprint toe edge	59.98%	5.88%	61.85%	61.85%	16
44	Push on the drying rack	Tense	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the footprint toe edge	0.9453m	0.113232	1.101m	1.101m	16
45	Push on the drying rack	Tense	Stretch out of hand refers to the subject height (%) allows the human centroid to reach the window frame	72.80%	10.99%	66.85%	66.85%	16
46	Push on the drying rack	Tense	Stretch out of hand refers to the subject height (m) allows the human centroid to reach the window frame	1.1444m	0.167307	1.19m	1.19m	16
47	Push the window frame	Relax	% of subject weight push on the support allowing the human centroid to reach the footprint toe edge	22.942%	9.4016%	44.5%	9%	26
48	Push the window frame	Relax	loading push on the support allowing the human centroid to reach the footprint toe edge	14.70kg	7.86kg	34.94kg	8.20kg	26
49	Push the window frame	Relax	% of subject weight push on the support allowing the human centroid to reach the window frame	33.521%	14.223%	54%	14.5%	26
50	Push the window frame	Relax	loading push on the support allowing the human centroid to reach the window frame	21.35kg	11.05kg	44.87kg	13.20kg	26
51	Push the window frame	Tense	% of subject weight push on the support allowing the human centroid to reach the footprint toe edge	11.033%	1.3906%	13%	13%	3
52	Push the window frame	Tense	loading push on the support allowing the human centroid to reach the footprint toe edge	7.30kg	2.10kg	10.21kg	10.21kg	3
53	Push the window frame	Tense	% of subject weight push on the support allowing the human centroid to reach the window frame	12.5%	1.4142%	14.5%	14.5%	3
54	Push the window frame	Tense	loading push on the support allowing the human centroid to reach the window frame	8.25kg	2.26kg	11.39kg	11.39kg	3
55	Push on the drying rack	Relax	% of subject weight push on the support allowing the human centroid to reach the footprint toe edge	11.41%	4.3725%	18%	7.5%	26
56	Push on the drying rack	Relax	loading push on the support allowing the human centroid to reach the footprint toe edge	7.62kg	3.92kg	14.13kg	4.09kg	26
57	Push on the drying rack	Relax	% of subject weight push on the support allowing the human centroid to reach the window frame	19.173%	8.3642%	20.5%	12%	26
58	Push on the drying rack	Relax	loading push on the support allowing the human centroid to reach the window frame	12.68kg	6.76kg	16.10kg	6.55kg	26
59	Push on the drying rack	Tense	% of subject weight push on the support allowing the human centroid to reach the footprint toe edge	10.5%	1.5%	12%	12%	2
60	Push on the drying rack	Tense	loading push on the support allowing the human centroid to reach the footprint toe edge	7.42kg	2.00kg	9.42kg	9.42kg	2
61	Push on the drying rack	Tense	% of subject weight push on the support allowing the human centroid to reach the window frame	12%	1%	13%	13%	2
62	Push on the drying rack	Tense	loading push on the support allowing the human centroid to reach the window frame	8.42kg	1.79kg	10.21kg	10.21kg	2