Human Stability on Step Ladders

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ABSTRACT
This paper provides initial results of a set of experiments pertain to the stability of humans as they stand on a flat horizontal platform and on a narrow horizontal plank. As expected humans' stability depends on the part of the foot which supports their body, the availability of a reference and the width of the supporting surface. The results have direct applicability to the stability of workers on step ladders, beams and narrow platforms.

Keywords
Human Balance, Balance on ladders, Ladder Accidents.

1. INTRODUCTION
Balance is the ability to maintain the body's center of mass over its base of support [1] - the convex hull encompassing the contact area of the feet [2]. A properly functioning balance system allows humans to see clearly while moving, identify orientation with respect to gravity, determine direction and speed of movement, and make automatic postural adjustments to maintain posture and stability in various conditions and activities. When the center of gravity's projection on the supporting surface falls outside the feet's contact area human loose their balance. Humans have the inherent ability to sense this threat to and to use a complex set of sensorimotor control systems, that include sensory input from vision (sight), proprioception (touch), and the vestibular system (motion, equilibrium, spatial orientation) to prevent falling [2].

Falls are the leading cause of accidental death and the leading cause of injury admission to acute-care hospitals in seniors. In the United States alone, falls result in nearly 300,000 hip fractures per year, with associated health care costs of US$10 billion. With the "graying" of the baby-boom generation, projections indicate that fall-related problems such as hip fractures will quadruple over the next 40 years [3].

Stepladders are commonly being used by professionals and individuals as a mean to access elevated work areas. Step ladders are freestanding, light weight, relatively compact and easy to move from one work area to another. Based on US CPSC-NEISS (United States Consumer Product Safety Commission - National Electronic Injury Surveillance System) data, ladder accidents led to over 187,000 injuries requiring a hospital visit in 2009. A fall from a ladder obviously provides a higher risk of serious injury compared to a fall while standing on ground. Compared to solid ground, stepladders typically present a smaller and less rigid surface on which to stand, making loss of balance more likely and recovery more difficult. In addition, the user's base of support is reduced, since he is standing on a relatively narrow step (typically about 3" deep); this means that the user's center of gravity will be closer to his limit of stability [4].

A research regarding to the effects of height, surface firmness and visual influence on balance control where subjects sway was recorded at three different heights (ground, 3m and 9m) on different type of grounds (firm ground or foam pad) and with or without goggles restricting visual field, was reported in [5] The results of this investigation show that at 3m and 9m height without close visual references (meaning with the goggles) the anterior-posterior sway and the area of sway were significantly increased and close visual references reduced the sway [5].

In another study the effect of light touch to a fixed reference on humans' stability was investigated. During this study subjects stood on a force platform in a heel-to-toes stance to challenge their balance while touching a small force plate designed to measure the forces applied by on finger. Subjects were tested with eyes opened and eyes closed in three contact conditions: no contact, a light contact and a force contact. Results show that the average displacement of the center of mass was highest with no contact/eyes closed and reduced in all other conditions. Despite mean fingertip force levels that were more than ten times greater with force that touch contact, light touch reduced sway equivalently [6].

In another study, the conditions of the "lift-off" of a stepladder were investigated. Subjects were asked to transfer weight, with arms crossed in front of the chest, form bipedal stance onto one foot at three different speeds: "at comfortable speed", "as fast as possible" and "at half your comfortable speed", at different height (on the ground and three different threads) and with different distance between the foot of stance and the ipsilateral rail. The results show that the size of the feasible no lift-off region (depending of the displacement of the Center of Mass (COM) related to the center of the Base of Support and the initial COM velocity) was inversely proportional to the height of the thread and the distance of the stand foot from the ipsilateral rail of the ladder [7].

These studies and a large number of others investigated the effect of different factors, such as vision proprioception and height, on humans' stability. Some also investigated the stability on stepladder parameters [7]. In this study humans' stability was investigated while subjects stand on a step ladder by tracking the movement of their center of gravity using force platform mounted under the ladder's feet.

This report describes the experiments, methods and the results of the experiments as well as the conclusions recommendations for changes in the structure of typical step ladder.

2. EXPERIMENTAL METHODOLOGY

The main thrust of the experiments was to determine the balance (stability) of the subjects by tracing the movements of their center of gravity as they perform a certain task.

For this purpose four force sensors were used for three sets of experiments:

1. **Establishing baseline:** In this case the four force sensors were supporting the corner of a plate on which subjects were standing.
2. **Standing on a narrow plank:** A narrow plank with the dimensions of the 4th rung of a 6 foot step ladder was installed on the above plate (Figure 1).
3. **Standing on a Step ladder:** The four force sensors were placed under the foot of a 6 foot step ladder.

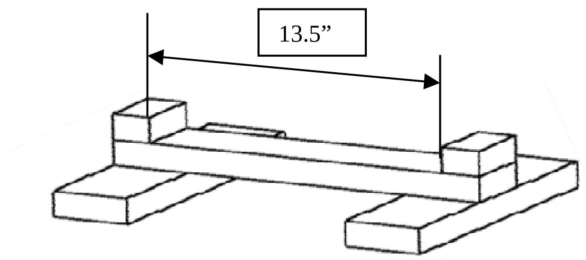

Figure 1: 4th rung of a 6 foot stepladder.

Eight subjects performed the experiments detailed in the following. The information about the subjects is listed in Table 1.

Table 1: Subjects’ data

Subject	Weight [kg]	Height [m]	Age [year]	Gender
1	70	1.70	21	F
2	75	1.97	21	M
3	66	1.78	23	M
4	68.4	1.57	63	M
5	81	1.82	41	M
6	59	1.68	46	F
7	97	1.95	59	M
8	70	1.65	19	F

At each experiment the four force were sampled at 100Hz for 10 seconds and the signals were filtered by a first order low pass filter with time constant of 0.25 second. An example of the signal is shown in Figure 2.

The location of the center of gravity was determined by simple moment equation about two perpendicular axes.

The location of the center of gravity was drawn on a polar plot with the origin at the centroid of the data. An example is shown in Figure 3.

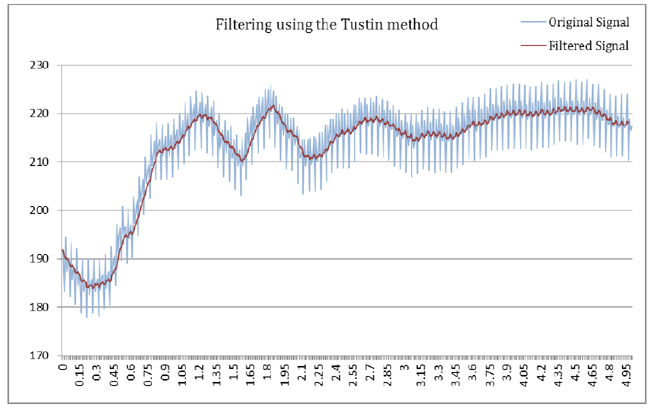

Figure 2: An example of the force signal.

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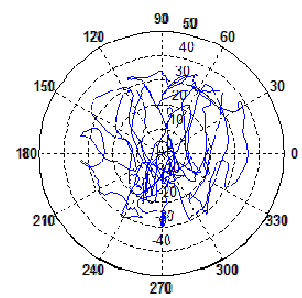

Figure 3: An example of a polar plot describing the location of the subjects’ center of gravity.

The radial scale of the polar plot was divided to 10 divisions (5mm apart) and a single value criteria indicating the balance of the subject was established as:

$$I = \frac{1}{1000} \sum_{i=1}^{10} n_i i^2 \tag{1}$$

where n_i is the number of data point falling within one division on the radial axis.

3. EXPERIMENTS

3.1 Establishing baseline

In this set of experiments, subjects were asked to stand still for ten seconds in three settings:

1. Open eyes looking forward.
2. Open eyes looking upward.
3. Closed eyes.

These tests were repeated for two cases: once the feet are tight together and second where the legs are spread to the maximum allowed by the 4th rung of a 6 foot step ladder (see Figure 1)

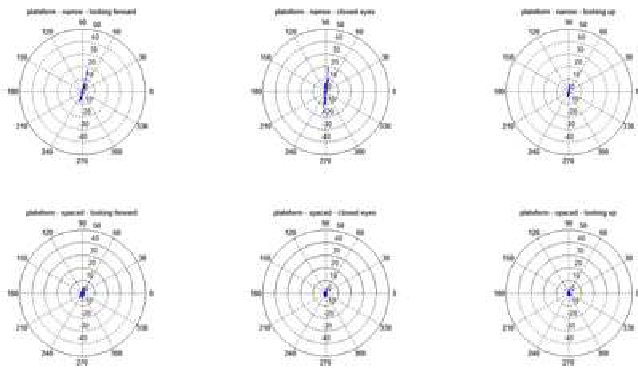

Figure 3: An example of test's results for baseline.

As shown in Figure 3, as the subject was looking upward, a situation occurs many times while using step ladder, its stability is reduced. Although we do not expect a step ladder user to close his eyes, the results just show that visual reference, or other, improves the stability of human. Also, as expected,

3.2 Standing on a narrow plank

In this set of experiments, subjects were asked to stand still for ten seconds on 3" wide plank once where their feet are tight together and then where they are spread to maximum allowed by the width of the 4th rung on a six feet step ladder (see Figure 1). Each of these tests was repeated three times where the subject stood on his different part of the foot as shown in Figure 4.

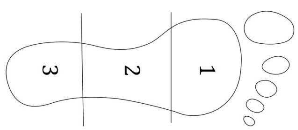

Figure 4: Standing zones.

3.3 Standing on a Step ladder:

In this set of experiments, subjects were standing on the 4th rung of a 6 foot step ladder. Subjects were asked to stand on the most convenient part of their feet. Three different scenarios were tested:

1. Leaning against the 5th rung (see Figure 5b).
2. Free standing (see Figure 5a).
3. Lightly touching a fixed point.

An example of the signals obtained by the force sensors is shown in Figure 6 where the marked zones correspond to the above scenarios.

As seen in Figure 6, the stability of the user provided a touch reference is better than the one who leans against the higher run and the free standing user

(a) (b)

Figure 5: Standing on a step ladder: a – free stand, b – leaning against the next rung.

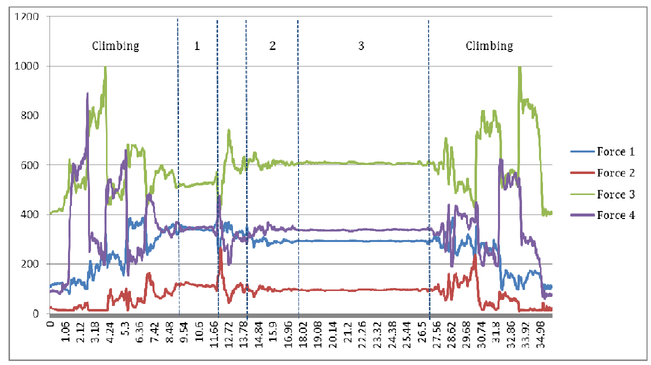

Figure 6: Force signals while sanding on a step ladder.

4. RESULTS

The performance index, I, as defined in Eq. 1 was determined for all test and the results are summarized in the following tables.

4.1 Baseline:

Table 2 provides the results of the tests performed for the establishment of baseline. It is clear the stability is enhanced when subjects are standing with their legs apart. However, the results, as pertained to vision scenarios, are not coherent.

Table 2: Standing on a platform.

	Looking Forward	Closed-eye	Looking Up
Feet together	2.13	3.93	1.48
Feet apart	0.68	0.58	0.80

4.2 Standing on a narrow plank:

The results of the second set of experiment where subjects were standing on a narrow plat using different zone of their feet are shown in Table 3.

Table 3: Standing on a narrow plank.

		Looking Forward	Closed eye	Looking Up
Feet together	Tip	5.93	15.70	7.37
	Middle	4.51	12.42	3.90
	Heel	5.08	17.67	4.85
Feet apart	Tip	6.08	10.93	3.92
	Middle	4.59	9.27	2.64
	Heel	4.53	13.88	4.00

Analyzing the results compiled in Table 3, few conclusions can be derived:

1. Standing with closed eyes is the most dangerous.
2. Unexpected, the results while looking up seems to be more stable. The only explanation for these results is the that ceiling of the room where the tests were conducted are low and as a result the visual queues were by far closer to the subject.
3. Standing on the middle section of the foot caused better stability.

Table 4: Standing on a narrow plank sorted by subjects' age.

		Looking Forward		Closed eye		Looking Up	
		Under 25	Over 25	Under 25	Over 25	Under 25	Over 25
Feet together	Platform	2.08	2,19	4,14	3.72	1.10	1.86
	Tips	4.54	7,32	18,27	13.13	8.63	6.11
	Middle	2.38	6,64	10.16	14.67	1.83	5.97
	Heels	3.18	6,97	13.88	21.45	2.55	7.14
Feet apart	Platform	0.45	0,90	0,27	0.89	0.31	1.29
	Tips	4.36	7,80	14.32	7.55	3.25	4.59
	Middle	1.63	7,55	7.31	11.23	1.38	3.91
	Heels	2.60	6,47	12.71	15.06	5.56	2.43

Table 4 show the same results sorted by the subjects' age. As shown in most cases the stability of young subjects (under 25 year old) is better (highlighted cells).

Table 5 show the same results sorted by the subjects' gender. As shown in all cases the females demonstrated better stability than males.

Table 5: Standing on a narrow plank sorted by gender.

		Looking Forward		Closed-eye		Looking Up	
		F	M	F	M	F	M
Feet together	Platform	1,91	2,27	2,61	4,72	0,67	1,96
	Tips	3,35	7,48	12,63	18,64	3,70	10,44
	Middle	2,38	5,79	4,26	17,31	2,86	4,51
	Heels	2,54	6,60	10,22	22,31	2,19	6,27
Feet apart	Platform	0,24	0,94	0,14	0,85	0,08	1,23
	Tips	3,39	7,69	4,66	16,49	2,72	4,64
	Middle	0,58	6,99	3,84	12,52	0,64	3,84
	Heels	1,64	6,22	3,03	21,73	1,04	6,60

4.3 Standing on a Step ladder

Only few test were performs when subjects are standing on the 4th rung of a 6 foot step ladder. The results are summarized in Table 6.

Table 6: Standing on a step ladder.

	Leaning on the 5th rung	Free standing	Light touch of a fixed ref.
Male	1.79	3.35	0.30
Female	0.30	0.54	0.00
Under 25	0.37	1.44	0.30
Over 25	2.44	3.41	0.00

Light touch of a fixed reference enhances stability the most. This is difficult to provide while a user perform a task standing on a ladder. However, it is possible to design for leaning surface which will improve user's stability as will shown in the following.

5. CONCLUSIONS AND RECOMMENDATIONS

The number of subjects and tests in this initial study was very limited which is reflected in inconsistent data. In any case few conclusions can be drawn:

1. Since the stability of a user is better on a wide surface, the width of the rungs should be increased.
2. Since ANSI [8] requires that the user will not step on the 5th rung of a 6 foot ladder, this rung should be removed and the 4th rung should be designed as a platform (such a solution does exists for 8 foot step ladders).
3. The step ladder cap should be modified to provide a comfort surface to lean on.

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