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Ground reaction forces on stairs: effects of stair inclination and age

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Abstract

The goals of the study were to compare data of vertical ground reaction force (GRF) parameters during level walking, stair ascent and descent on three different stair inclinations and three different age groups. Twenty healthy subjects of three age groups (young 33.7 years; middle 63.6 years; old 76.5 years) were tested during the seven test conditions with 8–10 repetitions. Vertical forces were measured during two consecutive steps with force plates embedded in the walkway and the staircase. The results showed that during level walking the vertical GRF curves were very regular and repetitive, the trail-to-trial variability and left–right asymmetry of defined test parameters being around 2–5% and 3–5%. During stair ascent the vertical GRF force pattern was found to change slightly compared to level gait, but considerably compared to stair descent. On the steep stair the average vertical load increased up to 1.6 BW, and variability (5–10%) and asymmetry (5–15%) were increased significantly. The steep stair descent condition was found to be the most demanding test showing the largest variability and asymmetry and thus, the least stable gait pattern. Age was found to be a factor which should be considered, because the young age group walked faster and produced larger vertical GRF maxima during level walking and on stair ascent than the middle and old age group. Differences between the middle and old age group were found to be small. The present investigation is the first to provide normative data of GRF parameters on gait variability and symmetry of two consecutive steps during level gait and stair ambulation. It is the intention that the results of this study may be used as a basis for comparison with patient data.

Keywords: Gait analysis; Stairs; Force curves; Variability; Symmetry

1. Introduction

Stairs are often considered as an obstacle and are a major cause for falls and accidents in the elderly population [1,2]. Research on stair ambulation is limited, however, and is rare with respect to ground reaction force (GRF) measurements during stair ascent and descent.

Gait analysis of level walking has a longstanding tradition in biomechanics [3]. One important aspect of it is the measurement of the vertical GRF and the interpretation of its characteristic "M" shaped curve [4,5]. Parameterization of distinct points on the GRF curve [6] has been pursued by a number of authors (Table 2) concerned with gait symmetry [7–10]. In level walking, the vertical GRF curve is generally known to be highly repeatable within individuals [10–12].

During stair ascent and descent, compared to level walking, little is known whether the shape of the vertical GRF curve may be equally characteristic and reproducible, and whether the GRF is dependent on stair inclination and age. Furthermore, parameterization of the vertical GRF curve for stair data is presently not available. Consequently, gait symmetry data of normal subjects during stair ambulation is still unknown, but would be useful for comparisons with patient data [13].

The first two steps from level walking to stair ascent or descent have been described as a "transition" in which adjustments in control of motion are necessary before the subjects set into a steady state that continues over the following steps [1,12,14]. Thus, when aiming at the description of two consecutive steps in steady state on stairs, a minimum of five steps seems necessary. From this point of view, all but four previous studies [14–17] (Table 1) have used test stairs, which were too short [18–22].

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Table 1
Investigations on stair ascending and descending using stair embedded force plates

Authors	No. of steps	Riser height (cm)	Tread/run (cm)	Inclination (°)	No. of force plates
Andriacchi et al. (1980, 1982)[a,b]	3	21	25.5	39.5	1
Besser at al. [18][a]	3	22	25	41.3	2
Christina and Cavanagh [14]	7	18	28	32.7	2
Costigan et al. (2002)	3	20	20	33.7	1
Kaufman et al. [19][a,b]	4	18	25	35.8	2
Kelman et al. [20][a]	2	17.8	–	–	2
Kowalk et al. [21][a,b]	3	20.3	25.4	38.6	2
Lobo da Costa and Amadio [15]	5	21.5	40	30	2
McFadyen and Winter [16][a,b]	5	–	–	37	1
Riener et al. [17]	5	13.8–23.0	31.0–24.7	24–43	4
Savvidis and von der Decken [23]	4	17	–	–	1
Yu et al. [12,29][a,b]	4	18	25	35.8	3
Zachazewski et al. [22][a]	4	18	28	32.7	2

[a] Indicates that no force data can be deduced from this work.
[b] Indicates that moment data is reported.

Lastly, most previous investigations did not report GRF data, but data on kinematics, EMG or knee moments. In summary, normative data of GRF on stairs was found to be limited [14,15,17,23] and data that allows testing gait symmetry of two consecutive steps has not been reported yet.

Stair dimensions are based on a long architectural history but on very little experimental evidence [1,2]. Nevertheless, stair dimensions with a riser height of around 7 in./17.8 cm and a run of 11 in./29.9 cm run (i.e. 30.8° inclination) are widely used around the world. SUVA [24] has defined the dimensions of different types of stairs.

The first attempts to define distinct points on the vertical GRF curve were reported by Elftmann [25] and Drillis [26] the latter being the first to describe the slope of the force

Table 2
Gait parameters of force measurements defined by various studies

Authors	*N*	Activity	Fz2 (BW)	Fz3 (BW)	Fz4 (BW)	bn (BW/s)	en (BW/s)
Aebersold [35]	8n	Level				7.03 ± 1.18	5.24 ± 0.52
Borden at al. (1999)	9n	Level	1.02 ± 0.04		1.03 ± 0.05		
Christina and Cavanagh [14]	12y	Stair dn1	1.40 ± 0.20		0.96 ± 0.10	13.87 ± 4.36	
	12y	Stair dn2	1.48 ± 0.20		0.93 ± 0.11	14.01 ± 4.35	
	12o	Stair dn1	1.43 ± 0.20		0.97 ± 0.13	14.46 ± 4.58	
	12o	Stair dn2	1.50 ± 0.27		0.93 ± 0.13	15.97 ± 5.75	
Chao et al. [28]	52m	Level	1.13 ± 0.08	0.72 ± 0.11	1.12 ± 0.08		
	55f	Level	1.08 ± 0.08	0.75 ± 0.08	1.12 ± 0.08		
Giakas and Baltzopoulos [8]	10n	Level left	1.18 ± 0.08	0.76 ± 0.05	1.07 ± 0.04		
	10n	Level right	1.17 ± 0.10	0.75 ± 0.07	1.12 ± 0.06		
McCrory et al. [9]	35n	Level	1.05 ± 0.04		1.02 ± 0.04	5.22 ± 2.12	6.12 ± 2.19
Lobo da Costa and Amadio [15]	6c	Level	1.32				
	6c	Stair up			1.42		
	6c	Stair dn	2.06				
Nigg and Skleryk [30]	23o	Level	1.04 ± 0.13		0.99 ± 0.10		
Perry [5]		Level	1.10	0.80	1.10		
Riener et al. [17]	10n	Stair 24° up			1.03 ap		
		Stair 24° dn	1.26 ap				
		Stair 30° up					
		Stair 30° dn	1.32 ap		1.03 ap		
		Stair 42° up					
		Stair 42° dn	1.43 ap		1.04 ap		
Savvidis and von der Decken [23]	15up	Stair	1.2–1.7				
	15dn		<2.6				
White et al. [10]	15c	Level left	1.25 ± 0.12	0.54 ± 0.08	1.13 ± 0.08		
		Level right	1.25 ± 0.12	0.54 ±0.08	1.10 ± 0.09		

n: normals; m: male; f: female; y: young; o: old; c: children; dn1: first step down; dn2: second step down; ap: approximation.