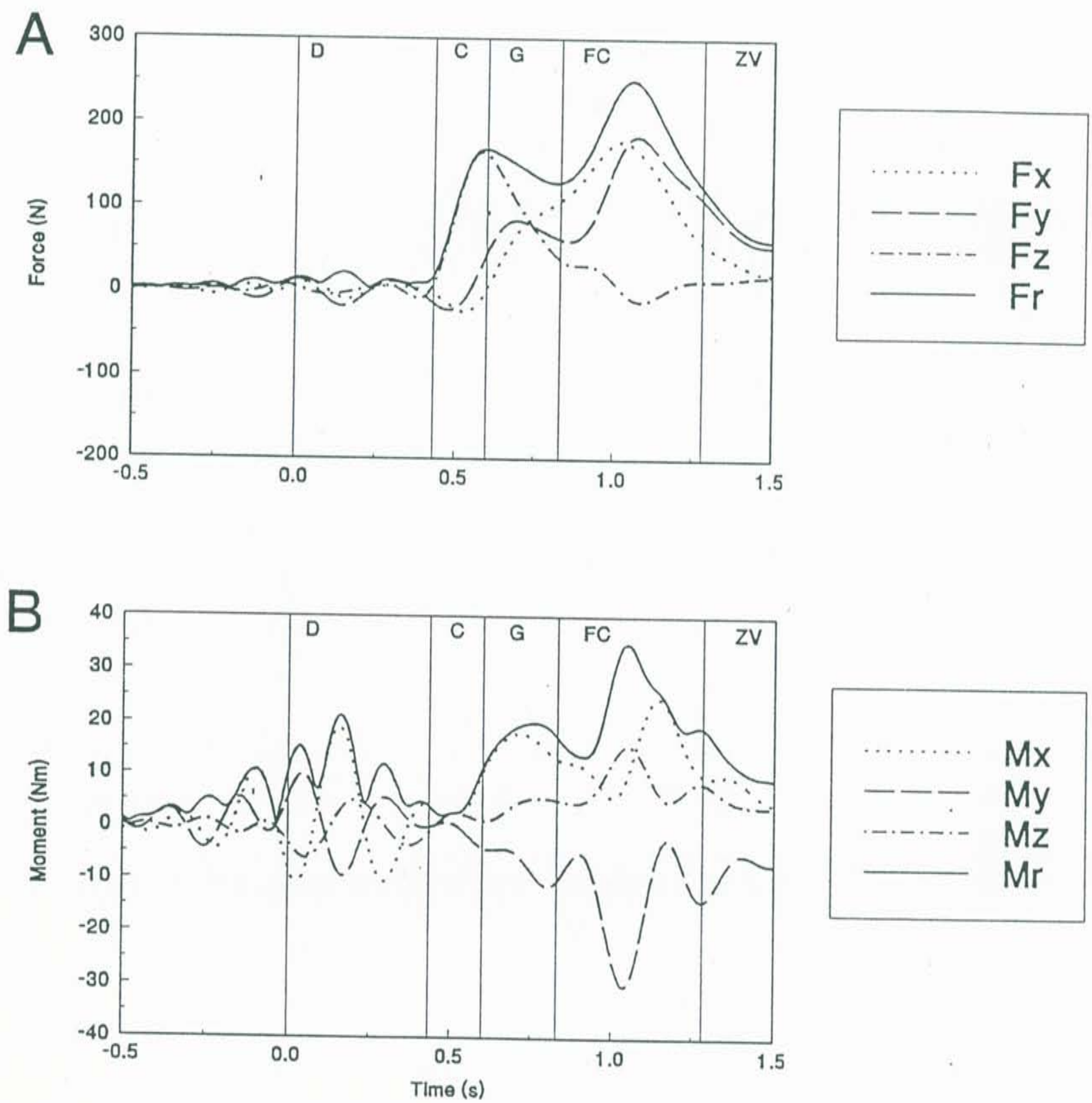

Figure 3.2 - Data from a representative main-experiment trial: grasp and step response; task conditions - medium perturbation, "close" position, left stance leg; see the explanatory note following Figure 3.4 for figure details.

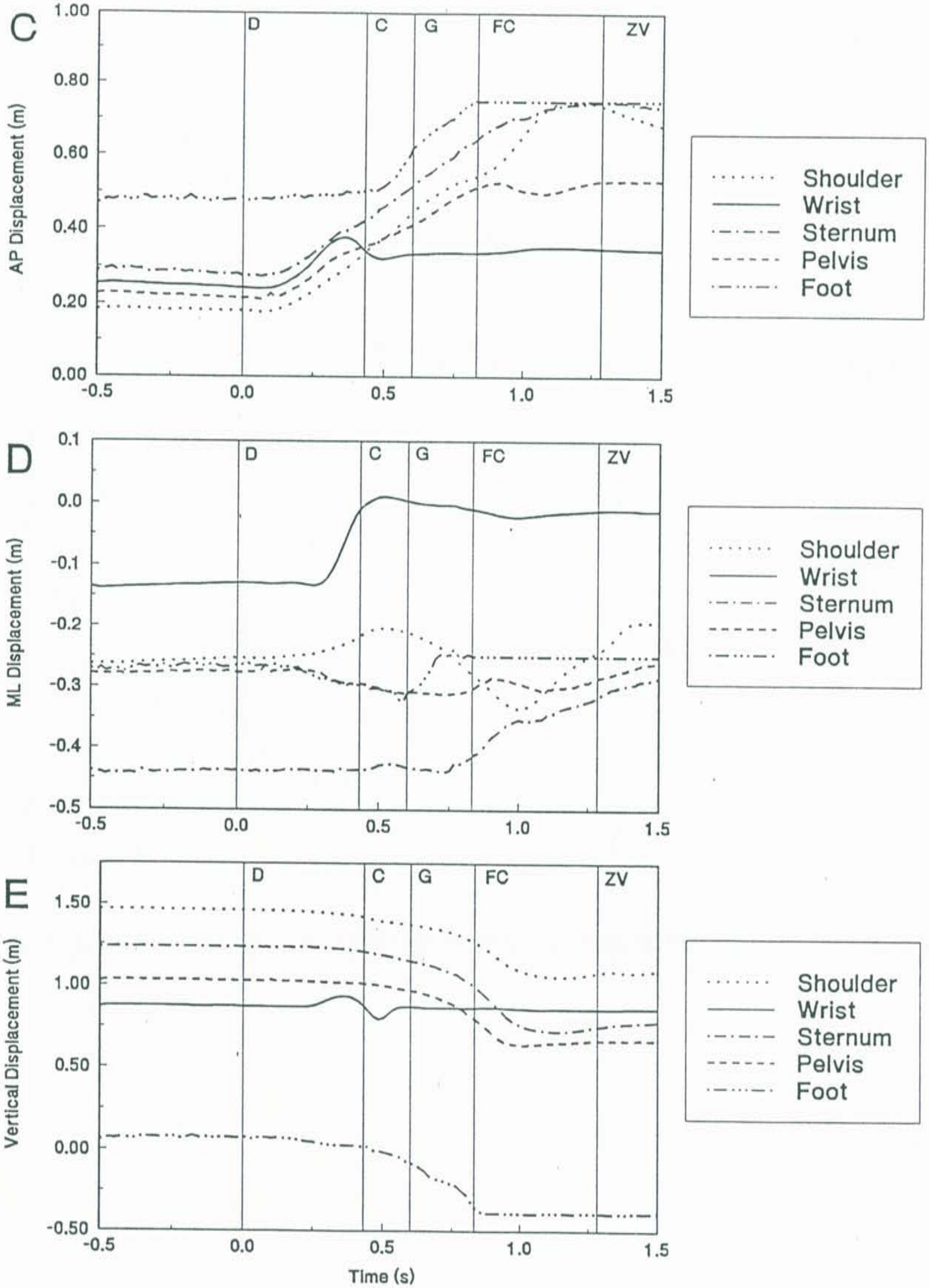

Figure 3.2 continued

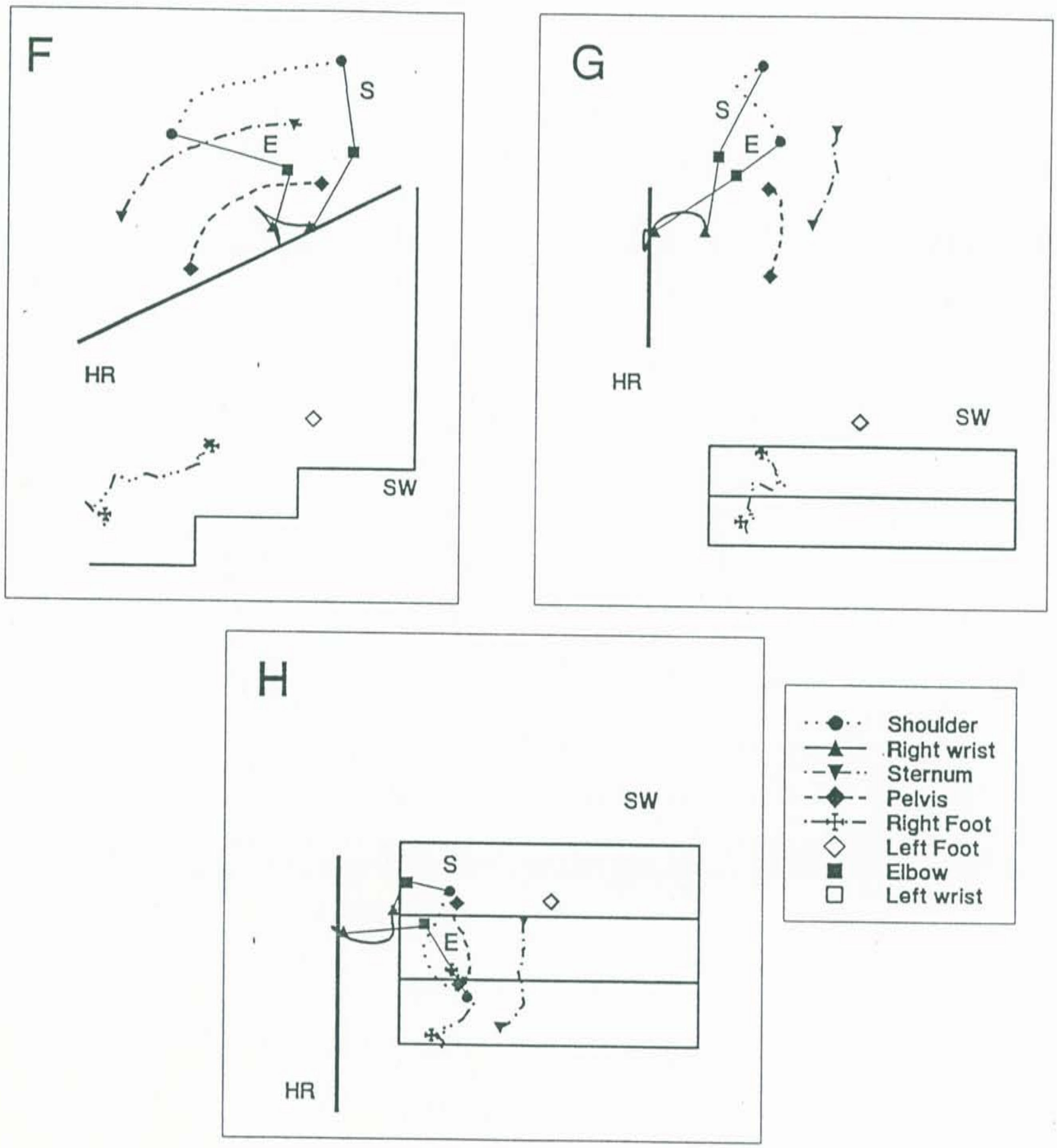

Figure 3.2 continued

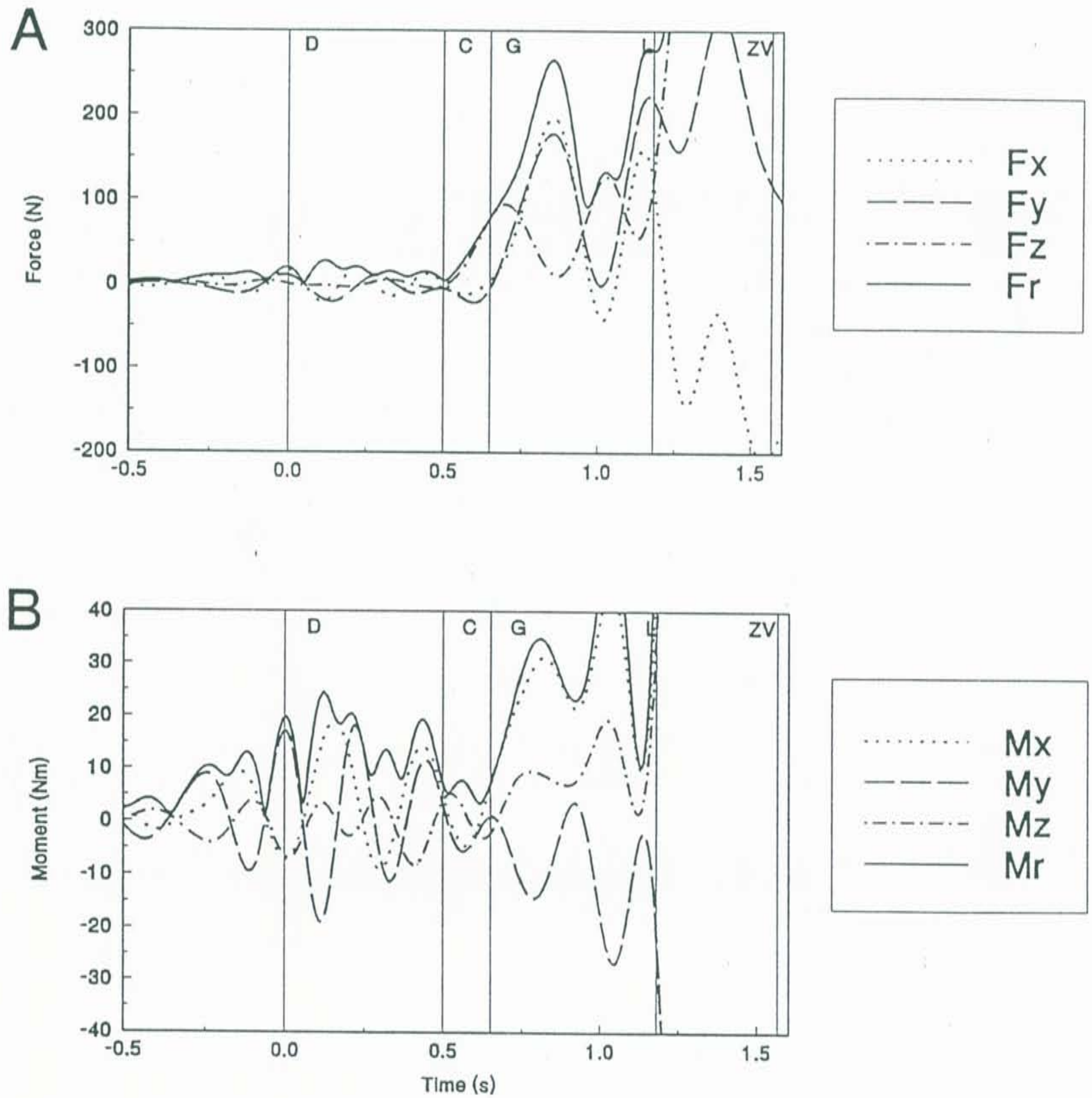

Figure 3.3 - Data from an example feet-obstructed trial: grasp-only (no-step) response, plus subsequent grasping with the left hand; task conditions - medium perturbation, "far" position; see the explanatory note following Figure 3.4 for figure details.

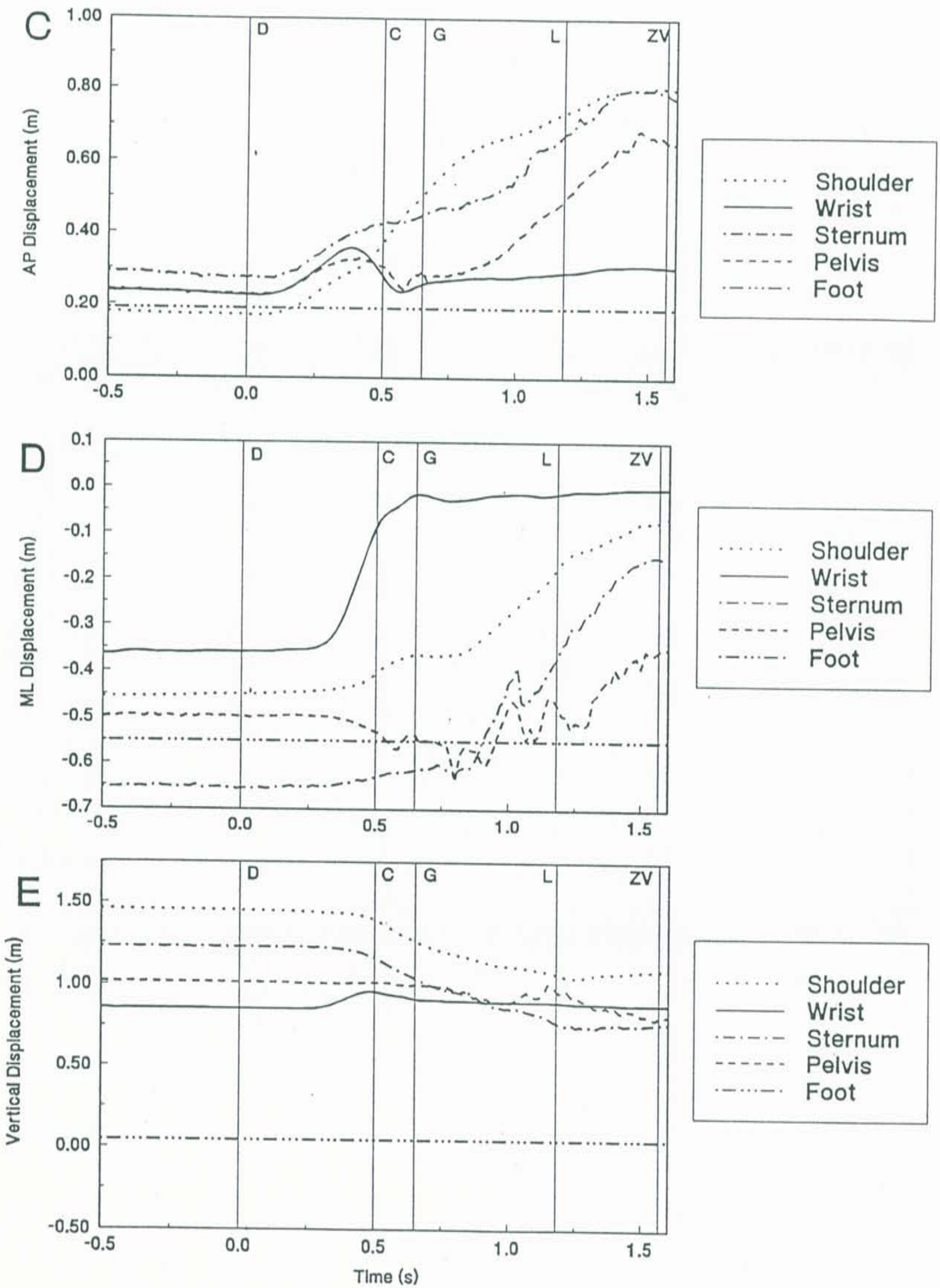

Figure 3.3 continued

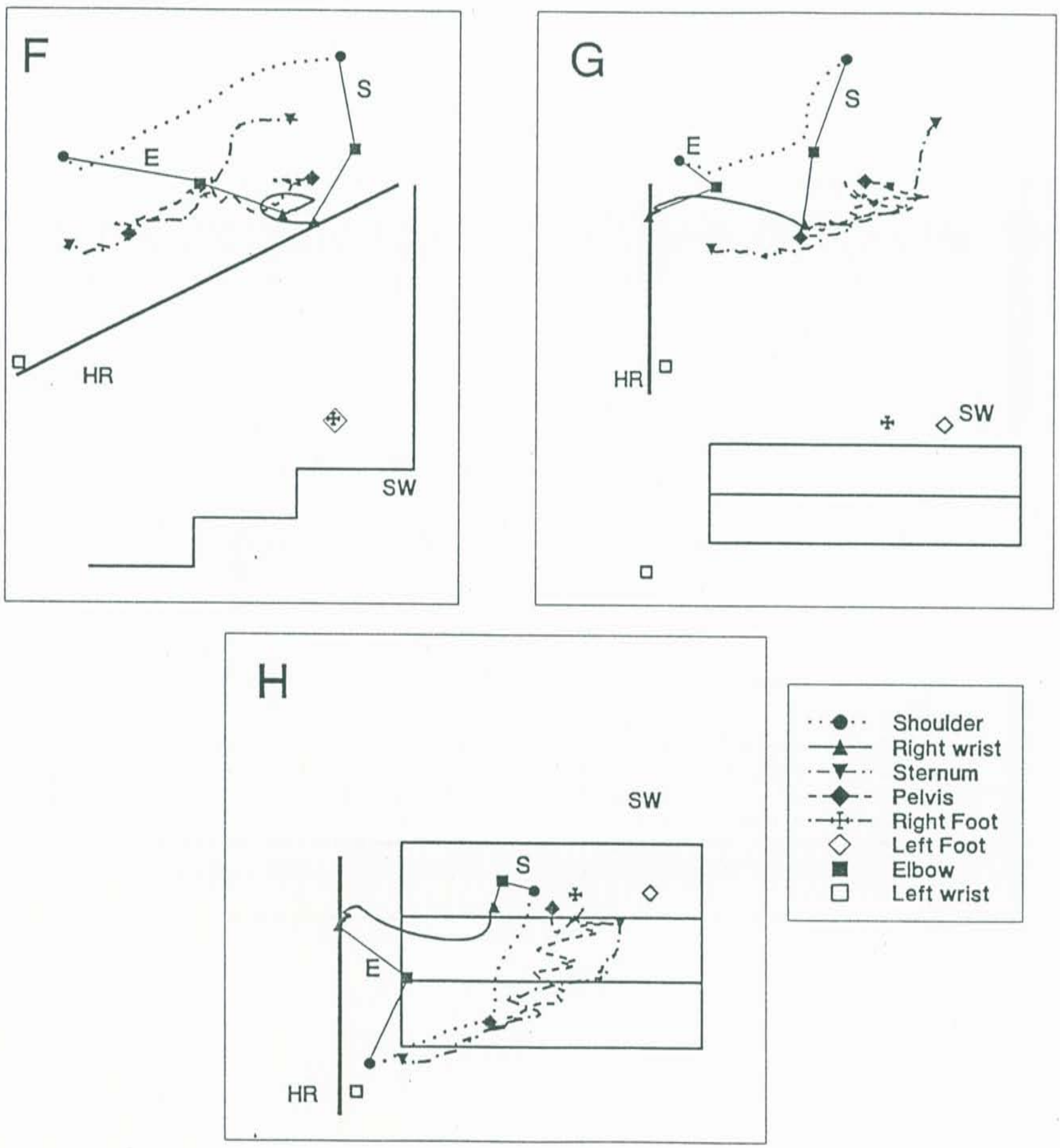

Figure 3.3 continued

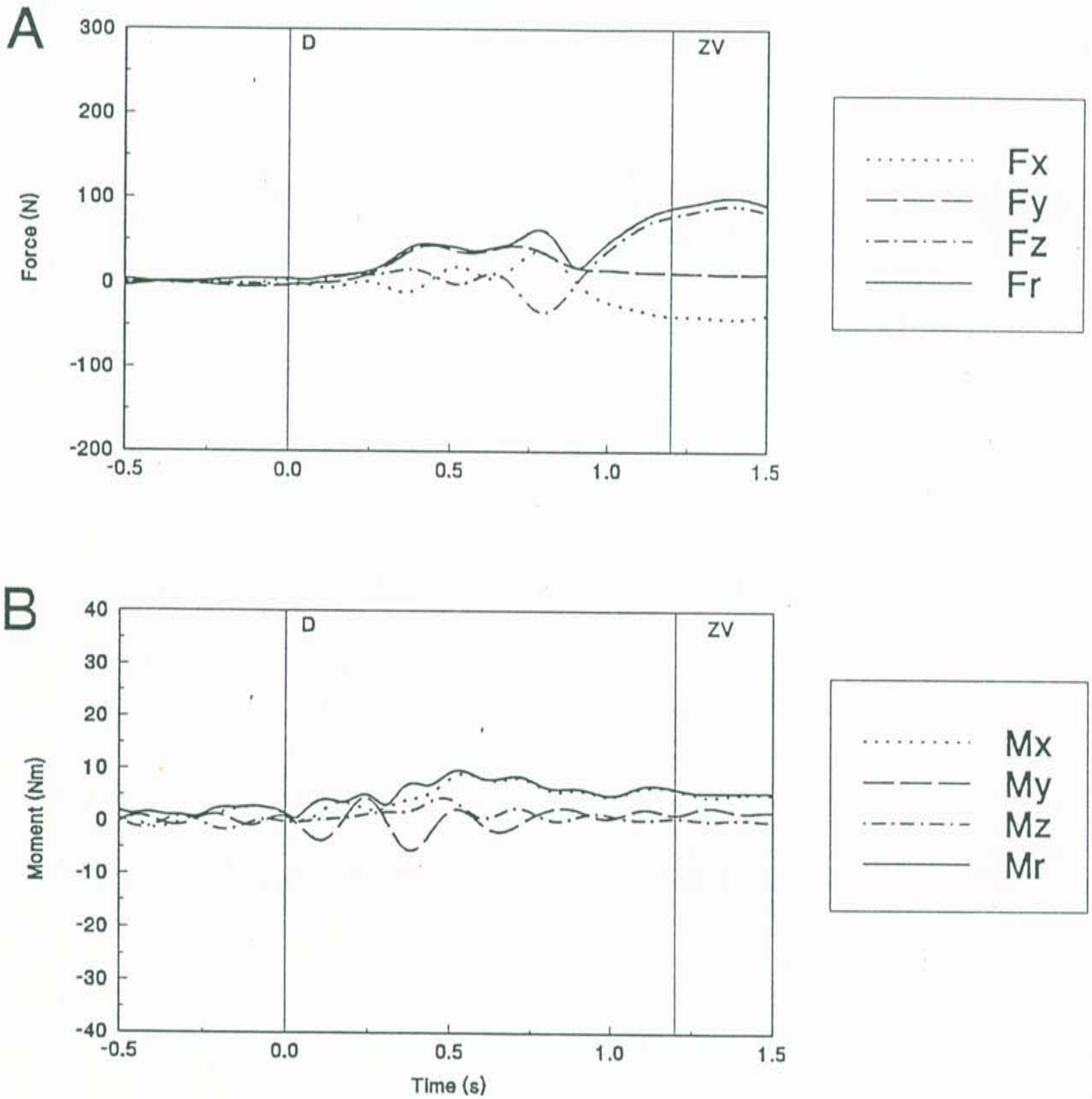

Figure 3.4 - Data from an example hand-on-rail trial: grasp-only (no-step) response; task conditions - small perturbation, "close" position, left stance leg; see the explanatory note following Figure 3.4 for figure details.

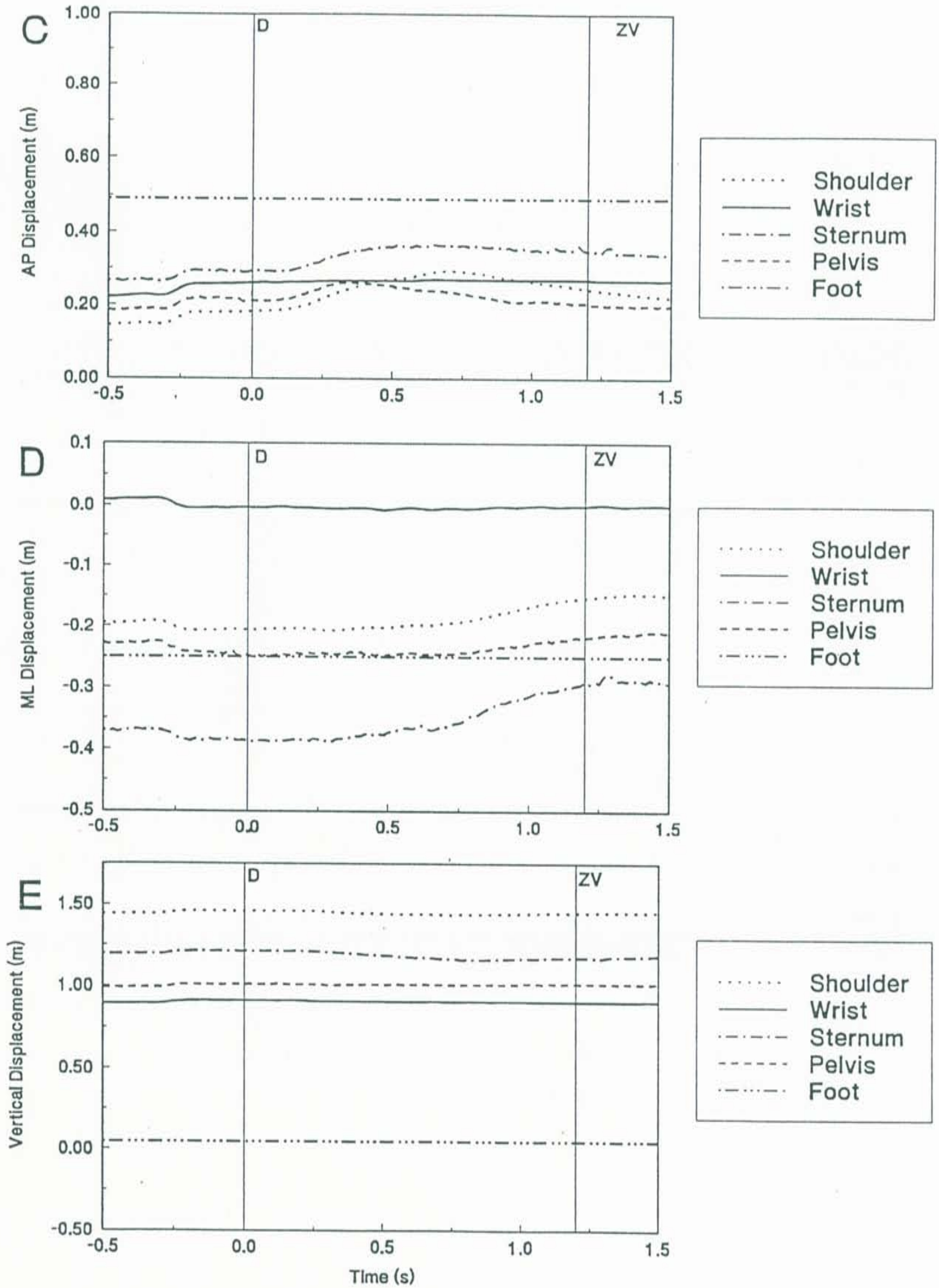

Figure 3.4 continued

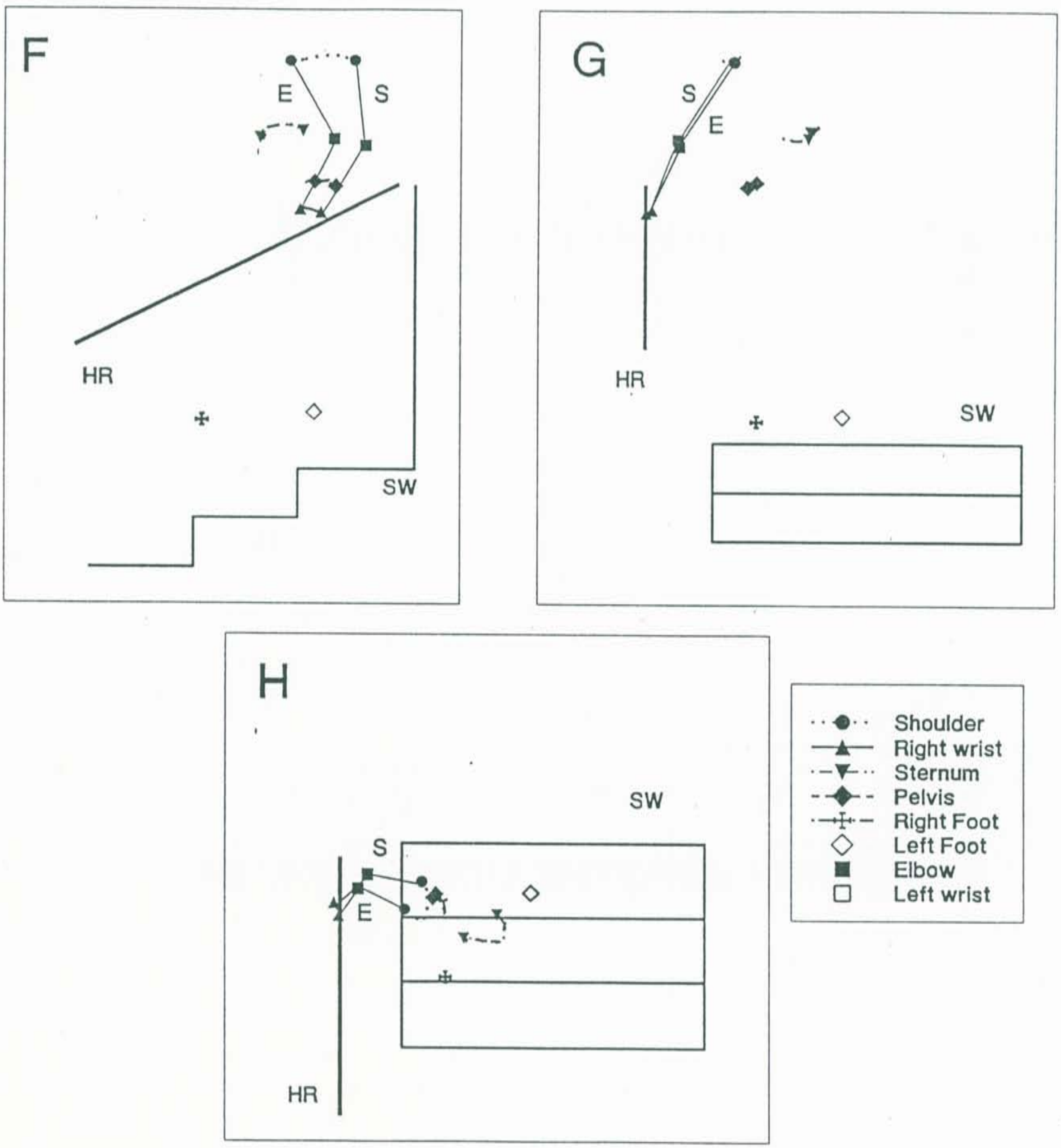

Figure 3.4 continued

Explanatory notes for Figures 3.1 to 3.4

1. The vertical lines shown in each plot are timing markers. The associated labels indicate onset of platform deceleration (D), initial contact with the handrail (C), full grasping of the handrail (G), and the point at which the body motion (i.e. the marker on the sternum) was estimated to reach zero velocity (ZV). In trials where stepping occurred, foot-contact of the swing foot with the bottom tread is also indicated (FC). In trials where the left hand grasped the handrail, onset of handrail contact is also indicated (L).

2. Panel A shows the m-l (Fx), a-p (Fy) and vertical (Fz) components of the resultant (Fr) handrail force. See Figure 2.5 for the definition of the axis directions and sign conventions.

3. Panel B shows the pure moments generated by the hand, about the m-l axis (Mx), the a-p axis (My) and the vertical axis (Mz), as well as the resultant moment (Mr). See Figure 2.5 for the definition of the axis directions and sign conventions. Note that the variations in the moments that occur prior to handrail contact (point C) are artifacts resulting primarily from the acceleration and deceleration of the platform.

4. Panel C shows the displacement of selected body markers, in the forward a-p direction, measured relative to the backboard. The markers were placed on the right shoulder (acromion), right wrist (dorsal surface, at the base of the hand), right side of the pelvis (right anterior superior iliac spine) and right foot (dorsal surface of the metatarsals), as well as the sternum.

5. Panel D shows the displacement of the same body markers in the m-l direction; the zero value corresponds to the center-line of the handrail; positive values indicate displacements to the subject's right.

6. Panel E shows the displacement of the same body markers in the vertical direction; the zero value corresponds to the surface of the top stair tread; positive coordinates are above the top stair tread, negative coordinates are below the top stair tread.

7. Panels F, G and H show the trajectories of the same body markers in the sagittal (a-p), frontal (m-l) and transverse (horizontal) planes, respectively. The left-foot marker is also shown in each of the plots. In Figure 3.3, the location of the left-hand grip on the handrail is also indicated. The lines connecting the shoulder, elbow and wrist markers indicate the arm position at the start of platform deceleration (label S) and at the end of the response, when equilibrium has been re-established (label E). The location of the mock stairway and backboard (label SW) and the handrail (label HR) are indicated schematically.

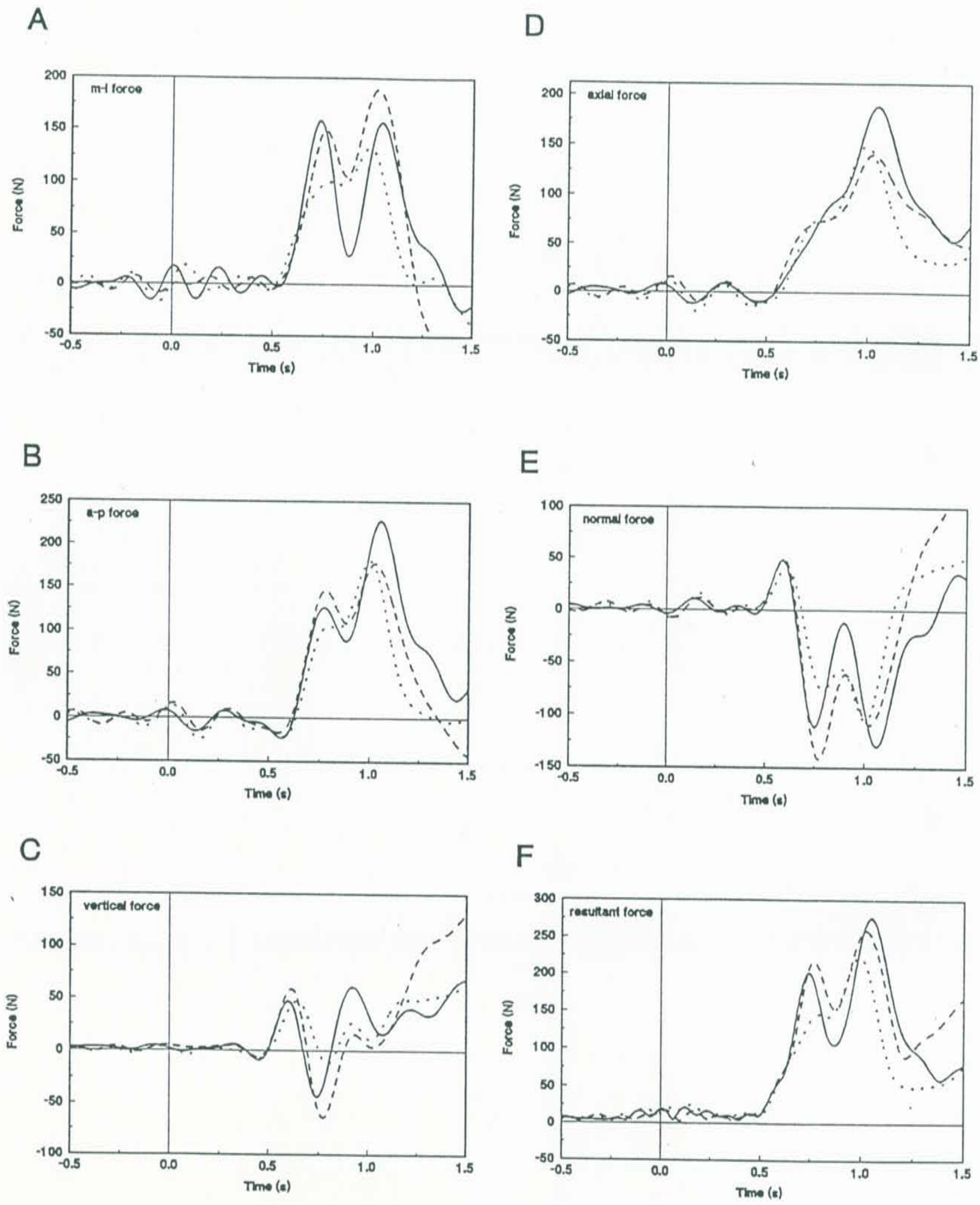

Figure 3.5 - Example data showing trial-to-trial variability in the force measurements; three trials, from the same subject, are shown in each plot; in each case, the subject responded by grasping the handrail and stepping; task conditions - medium perturbation, "far"position, left stance leg.

Table 3.1: Patterns of response

TASK	PERTURBATION MAGNITUDE	NUMBER OF TRIALS	FREQUENCY OF RESPONSE (% OF TRIALS)							
			"VALID" RESPONSES		"INVALID" RESPONSES					
			GRASP ONLY	GRASP AND STEP	STEP WITH "WRONG" FOOT	OVERSTEP BOTTOM TREAD	PUSH AGAINST TREAD COVER	GRAB PLATFORM WALLS	OTHER "INVALID" RESPONSE	EARLY ARM EMG
MAIN EXPERIMENT	1	48	54.2	29.2	4.2	0.0	4.2	0.0	4.2	4.2
	2	48	8.3	43.8	14.6	8.3	20.8	0.0	0.0	4.2
	3	48	0.0	31.3	22.9	12.5	6.3	4.2	2.1	20.8
	all	144	20.8	34.7	13.9	6.9	10.4	1.4	2.1	9.7
FEET-OBSTRUCTED TRIALS	1	8	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	8	62.5	12.5	0.0	0.0	12.5	0.0	12.5	0.0
	3	8	25.0	0.0	0.0	12.5	12.5	0.0	37.5	12.5
	all	24	62.5	4.2	0.0	4.2	8.3	0.0	16.7	4.2
HAND-ON-RAIL TRIALS	1	8	87.5	0.0	0.0	0.0	12.5	0.0	0.0	0.0
	2	8	37.5	12.5	12.5	0.0	37.5	0.0	0.0	0.0
	3	8	12.5	37.5	0.0	0.0	37.5	0.0	0.0	12.5
	all	24	45.8	16.7	4.2	0.0	29.2	0.0	0.0	4.2
ALL TASKS COMBINED	1	64	64.0	21.9	3.1	0.0	4.7	0.0	3.1	3.1
	2	64	18.8	35.9	12.5	6.3	21.9	0.0	1.6	3.1
	3	64	4.7	28.1	17.2	10.9	10.9	3.1	6.3	18.8
	all	192	29.2	28.6	10.9	5.7	12.5	1.0	3.7	8.3

NOTE: Responses listed as "invalid" were excluded from the subsequent analyses. The column labelled "early arm EMG" includes only those responses that were not excluded for the other reasons listed, i.e. it does not include all trials showing evidence of anticipatory arm-muscle activation.

Table 3.2a: Main experiment: peak handrail forces - absolute values

FORCE COMPONENT (Newtons)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	37	8	3	92	49	17	212
	2	25	23	0	150	61	28	306
	3	15	33	0	161	73	71	343
	all	77	64	3	124	66	17	343
M-L: to right (negative Fx)	1	22	8	18	23	10	10	44
	2	20	23	5	34	22	10	96
	3	12	33	3	45	21	17	102
	all	54	64	26	32	19	10	102
A-P: backward (negative Fy)	1	37	8	3	18	6	10	28
	2	20	23	5	22	7	10	38
	3	10	33	5	27	12	11	45
	all	67	64	13	21	8	10	45
A-P: forward (positive Fy)	1	37	8	3	90	45	13	177
	2	25	23	0	159	46	57	233
	3	15	33	0	220	62	96	329
	all	77	64	3	138	70	13	329
VERTICAL: up (negative Fz)	1	15	8	25	58	41	17	143
	2	8	23	17	56	41	12	138
	3	5	33	10	59	50	17	140
	all	28	64	52	57	41	12	143
VERTICAL: down (positive Fz)	1	37	8	3	90	48	10	193
	2	25	23	0	128	81	15	366
	3	15	33	0	169	140	18	537
	all	77	64	3	118	88	10	537
AXIAL: backward (negative Fa)	1	9	8	31	15	2	12	18
	2	1	23	24	16	–	16	16
	3	3	33	12	20	5	14	25
	all	13	64	67	16	4	12	25
AXIAL: forward (positive Fa)	1	38	8	2	99	45	11	165
	2	25	23	0	155	52	27	285
	3	15	33	0	196	76	76	391
	all	78	64	2	136	66	11	391
NORMAL: up (negative Fn)	1	31	8	9	68	52	10	190
	2	24	23	1	92	52	11	225
	3	15	33	0	134	58	39	260
	all	70	64	10	90	58	10	260
NORMAL: down (positive Fn)	1	40	8	0	52	30	11	118
	2	25	23	0	83	57	16	246
	3	15	33	0	115	103	10	376
	all	80	64	0	74	62	10	376
RESULTANT: (Fr)	1	40	8	0	141	60	25	281
	2	25	23	0	239	63	108	378
	3	15	33	0	301	102	209	542
	all	80	64	0	202	95	25	542

NOTE: See explanatory notes following Table 3.4c.

Table 3.2b: Main experiment: peak handrail forces - normalized values

FORCE COMPONENT (% of body weight)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	37	8	3	12.3	6.6	1.9	26.2
	2	25	23	0	19.5	7.8	4.9	40.1
	3	15	33	0	20.7	9.5	8.8	44.9
	all	77	64	3	16.3	8.4	1.9	44.9
M-L: to right (negative Fx)	1	22	8	18	3.0	1.2	1.2	5.1
	2	20	23	5	4.4	2.4	1.2	11.0
	3	12	33	3	5.6	2.4	2.3	11.6
	all	54	64	26	4.1	2.2	1.2	11.6
A-P: backward (negative Fy)	1	37	8	3	2.4	0.7	1.3	3.6
	2	20	23	5	2.9	1.1	1.4	6.7
	3	10	33	5	3.4	1.6	1.4	5.9
	all	67	64	13	2.7	1.0	1.3	6.7
A-P: forward (positive Fy)	1	37	8	3	11.5	5.4	2.3	21.9
	2	25	23	0	20.5	5.1	10.0	29.0
	3	15	33	0	28.1	6.8	12.6	37.4
	all	77	64	3	17.7	8.6	2.3	37.4
VERTICAL: up (negative Fz)	1	15	8	25	7.5	4.8	2.2	17.7
	2	8	23	17	7.4	5.4	1.5	17.0
	3	5	33	10	7.3	6.1	2.0	17.3
	all	28	64	52	7.5	5.0	1.5	17.7
VERTICAL: down (positive Fz)	1	37	8	3	11.3	5.4	1.8	21.9
	2	25	23	0	16.8	10.7	2.7	45.3
	3	15	33	0	21.4	16.0	2.2	61.0
	all	77	64	3	15.1	10.6	1.8	61.0
AXIAL: backward (negative Fa)	1	9	8	31	1.8	0.2	1.4	2.1
	2	1	23	24	1.8	—	1.8	1.8
	3	3	33	12	2.6	0.7	1.9	3.3
	all	13	64	67	2.0	0.5	1.4	3.3
AXIAL: forward (positive Fa)	1	38	8	2	12.4	5.1	2.0	19.0
	2	25	23	0	20.1	6.0	4.8	32.4
	3	15	33	0	25.0	8.4	9.9	44.4
	all	78	64	2	17.3	7.9	2.0	44.4
NORMAL: up (negative Fn)	1	31	8	9	8.8	6.3	1.4	23.5
	2	24	23	1	11.9	6.5	1.2	27.9
	3	15	33	0	17.0	6.7	5.1	32.2
	all	70	64	10	11.6	7.1	1.2	32.2
NORMAL: down (positive Fn)	1	40	8	0	6.7	3.5	1.5	15.5
	2	25	23	0	11.1	8.0	2.6	37.5
	3	15	33	0	14.4	11.7	1.3	42.8
	all	80	64	0	9.5	7.7	1.3	42.8
RESULTANT: (Fr)	1	40	8	0	18.3	7.1	4.4	34.8
	2	25	23	0	31.1	7.4	19.0	45.6
	3	15	33	0	38.3	11.0	26.7	61.6
	all	80	64	0	26.1	11.4	4.4	61.6

NOTE: See explanatory notes following Table 3.4c.

Table 3.2c: Main experiment: peak handrail forces - time of peak value

FORCE COMPONENT (timing in seconds)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	37	8	3	1.021	0.484	0.580	2.635
	2	25	23	0	0.920	0.263	0.520	1.720
	3	15	33	0	0.829	0.153	0.530	1.155
	all	77	64	3	0.951	0.378	0.520	2.635
M-L: to right (negative Fx)	1	22	8	18	1.067	0.541	0.455	2.190
	2	20	23	5	0.901	0.525	0.345	2.110
	3	12	33	3	1.001	0.338	0.510	1.385
	all	54	64	26	0.991	0.494	0.345	2.190
A-P: backward (negative Fy)	1	37	8	3	0.589	0.233	0.390	1.805
	2	20	23	5	0.521	0.158	0.365	1.110
	3	10	33	5	0.577	0.305	0.385	1.230
	all	67	64	13	0.567	0.225	0.365	1.805
A-P: forward (positive Fy)	1	37	8	3	1.092	0.509	0.570	2.650
	2	25	23	0	1.009	0.245	0.555	1.760
	3	15	33	0	0.886	0.146	0.620	1.170
	all	77	64	3	1.025	0.390	0.555	2.650
VERTICAL: up (negative Fz)	1	15	8	25	0.983	0.430	0.640	2.365
	2	8	23	17	0.848	0.202	0.610	1.115
	3	5	33	10	0.708	0.114	0.595	0.825
	all	28	64	52	0.896	0.346	0.595	2.365
VERTICAL: down (positive Fz)	1	37	8	3	0.988	0.442	0.480	2.070
	2	25	23	0	0.803	0.365	0.455	1.775
	3	15	33	0	0.772	0.285	0.415	1.270
	all	77	64	3	0.886	0.399	0.415	2.070
AXIAL: backward (negative Fa)	1	9	8	31	0.485	0.068	0.370	0.575
	2	1	23	24	0.365	——	0.365	0.365
	3	3	33	12	0.400	0.010	0.390	0.410
	all	13	64	67	0.456	0.072	0.365	0.575
AXIAL: forward (positive Fa)	1	38	8	2	1.089	0.471	0.565	2.410
	2	25	23	0	0.847	0.214	0.495	1.140
	3	15	33	0	0.766	0.146	0.500	0.955
	all	78	64	2	0.949	0.380	0.495	2.410
NORMAL: up (negative Fn)	1	31	8	9	1.116	0.539	0.635	2.685
	2	24	23	1	0.995	0.246	0.620	1.770
	3	15	33	0	0.873	0.162	0.610	1.190
	all	70	64	10	1.023	0.401	0.610	2.685
NORMAL: down (positive Fn)	1	40	8	0	0.910	0.446	0.465	2.205
	2	25	23	0	0.753	0.385	0.425	1.750
	3	15	33	0	0.812	0.331	0.410	1.265
	all	80	64	0	0.843	0.409	0.410	2.205
RESULTANT: (Fr)	1	40	8	0	1.033	0.474	0.565	2.475
	2	25	23	0	0.882	0.224	0.465	1.205
	3	15	33	0	0.747	0.134	0.495	0.890
	all	80	64	0	0.932	0.377	0.465	2.475

NOTE: See explanatory notes following Table 3.4c.

Table 3.3a: Feet-obstructed trials: peak handrail forces - absolute values

FORCE COMPONENT (Newtons)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	8	0	0	76	58	21	192
	2	6	2	0	140	54	81	217
	3	2	6	0	112	48	79	146
	all	16	8	0	105	60	21	217
M-L: to right (negative Fx)	1	3	0	5	28	10	18	38
	2	2	2	4	67	35	42	92
	3	0	6	2	—	—	—	—
	all	5	8	11	44	29	18	92
A-P: backward (negative Fy)	1	5	0	3	23	8	13	31
	2	3	2	3	21	9	12	30
	3	2	6	0	17	10	10	24
	all	10	8	6	21	8	10	31
A-P: forward (positive Fy)	1	8	0	0	77	48	11	166
	2	6	2	0	210	47	142	261
	3	2	6	0	274	59	232	315
	all	16	8	0	151	91	11	315
VERTICAL: up (negative Fz)	1	4	0	4	80	82	11	178
	2	4	2	2	112	78	41	215
	3	2	6	0	103	4	101	106
	all	10	8	6	97	67	11	215
VERTICAL: down (positive Fz)	1	7	0	1	62	36	10	113
	2	5	2	1	132	89	62	242
	3	0	6	2	—	—	—	—
	all	12	8	4	91	70	10	242
AXIAL: backward (negative Fa)	1	1	0	7	13	—	13	13
	2	1	2	5	24	—	24	24
	3	1	6	1	18	—	18	18
	all	3	8	13	18	5	13	24
AXIAL: forward (positive Fa)	1	8	0	0	63	30	19	107
	2	6	2	0	166	86	61	299
	3	2	6	0	163	31	142	185
	all	16	8	0	114	76	19	299
NORMAL: up (negative Fn)	1	5	0	3	111	89	29	243
	2	6	2	0	174	95	73	323
	3	2	6	0	243	51	207	279
	all	13	8	3	160	94	29	323
NORMAL: down (positive Fn)	1	6	0	2	47	17	18	63
	2	5	2	1	58	35	19	97
	3	2	6	0	15	4	12	17
	all	13	8	3	46	28	12	97
RESULTANT: (Fr)	1	8	0	0	131	84	35	259
	2	6	2	0	268	76	173	346
	3	2	6	0	304	82	246	362
	all	16	8	0	204	107	35	362

NOTE: See explanatory notes following Table 3.4c.

Table 3.3b: Feet-obstructed trials: peak handrail forces - normalized values

FORCE COMPONENT (% of body weight)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	8	0	0	10.0	7.0	2.4	23.8
	2	6	2	0	18.2	6.3	12.8	26.8
	3	2	6	0	15.2	1.9	13.9	16.6
	all	16	8	0	13.7	7.2	2.4	26.8
M-L: to right (negative Fx)	1	3	0	5	3.5	1.4	2.0	4.9
	2	2	2	4	8.8	4.6	5.5	12.1
	3	0	6	2	—	—	—	—
	all	5	8	11	5.6	3.9	2.0	12.1
A-P: backward (negative Fy)	1	5	0	3	3.0	1.0	1.4	4.1
	2	3	2	3	2.6	1.0	1.6	3.4
	3	2	6	0	2.3	0.7	1.8	2.8
	all	10	8	6	2.7	0.9	1.4	4.1
A-P: forward (positive Fy)	1	8	0	0	9.8	5.8	1.9	20.5
	2	6	2	0	27.7	6.2	16.1	34.2
	3	2	6	0	38.3	3.5	35.8	40.8
	all	16	8	0	20.1	12.4	1.9	40.8
VERTICAL: up (negative Fz)	1	4	0	4	9.9	10.1	1.5	22.1
	2	4	2	2	14.4	9.0	7.2	26.7
	3	2	6	0	14.9	4.0	12.0	17.7
	all	10	8	6	12.7	8.3	1.5	26.7
VERTICAL: down (positive Fz)	1	7	0	1	7.8	4.0	1.8	12.8
	2	5	2	1	17.5	11.5	7.7	31.7
	3	0	6	2	—	—	—	—
	all	12	8	4	11.9	9.0	1.8	31.7
AXIAL: backward (negative Fa)	1	1	0	7	1.7	—	1.7	1.7
	2	1	2	5	2.7	—	2.7	2.7
	3	1	6	1	2.0	—	2.0	2.0
	all	3	8	13	2.1	0.5	1.7	2.7
AXIAL: forward (positive Fa)	1	8	0	0	8.0	3.0	3.4	12.1
	2	6	2	0	22.0	11.3	7.5	39.1
	3	2	6	0	23.0	2.8	21.0	24.9
	all	16	8	0	15.1	10.1	3.4	39.1
NORMAL: up (negative Fn)	1	5	0	3	14.2	10.6	5.2	30.1
	2	6	2	0	22.8	11.4	8.3	40.0
	3	2	6	0	34.0	3.4	31.7	36.4
	all	13	8	3	21.2	11.9	5.2	40.0
NORMAL: down (positive Fn)	1	6	0	2	6.0	1.9	3.2	7.8
	2	5	2	1	7.6	4.5	3.0	12.7
	3	2	6	0	2.0	0.1	1.9	2.1
	all	13	8	3	6.0	3.5	1.9	12.7
RESULTANT: (Fr)	1	8	0	0	16.7	9.9	6.2	32.1
	2	6	2	0	35.2	8.6	19.7	42.8
	3	2	6	0	42.3	1.6	41.1	43.4
	all	16	8	0	26.8	13.6	6.2	43.4

NOTE: See explanatory notes following Table 3.4c.

Table 3.3c: Feet-obstructed trials: peak handrail forces - time of peak value

FORCE COMPONENT (timing in seconds)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	8	0	0	0.752	0.104	0.620	0.935
	2	6	2	0	0.915	0.285	0.610	1.440
	3	2	6	0	0.783	0.251	0.605	0.960
	all	16	8	0	0.817	0.206	0.605	1.440
M-L: to right (negative Fx)	1	3	0	5	1.455	0.569	1.005	2.095
	2	2	2	4	1.765	1.082	1.000	2.530
	3	0	6	2	—	—	—	—
	all	5	8	11	1.579	0.695	1.000	2.530
A-P: backward (negative Fy)	1	5	0	3	0.611	0.091	0.515	0.720
	2	3	2	3	0.478	0.089	0.415	0.580
	3	2	6	0	0.400	0.014	0.390	0.410
	all	10	8	6	0.529	0.117	0.390	0.720
A-P: forward (positive Fy)	1	8	0	0	0.827	0.080	0.690	0.905
	2	6	2	0	1.146	0.625	0.600	2.225
	3	2	6	0	0.815	0.290	0.610	1.020
	all	16	8	0	0.945	0.406	0.600	2.225
VERTICAL: up (negative Fz)	1	4	0	4	0.767	0.066	0.695	0.855
	2	4	2	2	0.939	0.438	0.690	1.595
	3	2	6	0	0.772	0.251	0.595	0.950
	all	10	8	6	0.837	0.283	0.595	1.595
VERTICAL: down (positive Fz)	1	7	0	1	1.053	0.718	0.575	2.615
	2	5	2	1	1.213	0.801	0.550	2.530
	3	0	6	2	—	—	—	—
	all	12	8	4	1.120	0.722	0.550	2.615
AXIAL: backward (negative Fa)	1	1	0	7	0.485	—	0.485	0.485
	2	1	2	5	0.405	—	0.405	0.405
	3	1	6	1	0.410	—	0.410	0.410
	all	3	8	13	0.433	0.045	0.405	0.485
AXIAL: forward (positive Fa)	1	8	0	0	0.910	0.206	0.615	1.265
	2	6	2	0	1.217	0.726	0.590	2.530
	3	2	6	0	0.820	0.283	0.620	1.020
	all	16	8	0	1.014	0.478	0.590	2.530
NORMAL: up (negative Fn)	1	5	0	3	0.799	0.074	0.690	0.865
	2	6	2	0	1.137	0.593	0.670	2.205
	3	2	6	0	0.793	0.265	0.605	0.980
	all	13	8	3	0.954	0.430	0.605	2.205
NORMAL: down (positive Fn)	1	6	0	2	1.105	0.781	0.560	2.630
	2	5	2	1	1.151	0.830	0.450	2.530
	3	2	6	0	0.400	0.014	0.390	0.410
	all	13	8	3	1.014	0.748	0.390	2.630
RESULTANT: (Fr)	1	8	0	0	0.818	0.123	0.685	1.005
	2	6	2	0	1.152	0.626	0.590	2.220
	3	2	6	0	0.805	0.276	0.610	1.000
	all	16	8	0	0.942	0.413	0.590	2.220

NOTE: See explanatory notes following Table 3.4c.

Table 3.4a: Hand-on-rail trials: peak handrail forces - absolute values

FORCE COMPONENT (Newtons)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	6	1	1	41	16	16	62
	2	4	4	0	70	38	14	100
	3	4	4	0	83	19	57	98
	all	14	9	1	61	30	14	100
M-L: to right (negative Fx)	1	3	1	4	22	14	14	38
	2	4	4	0	31	27	15	71
	3	4	4	0	33	5	29	41
	all	11	9	4	30	17	14	71
A-P: backward (negative Fy)	1	2	1	5	12	0	11	12
	2	2	4	2	27	5	23	30
	3	1	4	3	11	—	11	11
	all	5	9	10	18	9	11	30
A-P: forward (positive Fy)	1	7	1	0	57	32	23	118
	2	4	4	0	125	52	65	191
	3	4	4	0	176	31	137	211
	all	15	9	0	106	63	23	211
VERTICAL: up (negative Fz)	1	5	1	2	45	51	12	134
	2	3	4	1	149	78	84	236
	3	4	4	0	147	70	48	202
	all	12	9	3	105	79	12	236
VERTICAL: down (positive Fz)	1	7	1	0	72	74	11	190
	2	3	4	1	45	33	23	82
	3	4	4	0	73	60	27	161
	all	14	9	1	66	60	11	190
AXIAL: backward (negative Fa)	1	3	1	4	11	1	11	12
	2	2	4	2	26	1	25	27
	3	0	4	4	—	—	—	—
	all	5	9	10	17	8	11	27
AXIAL: forward (positive Fa)	1	7	1	0	76	59	25	171
	2	4	4	0	83	17	64	103
	3	4	4	0	102	21	73	120
	all	15	9	0	85	42	25	171
NORMAL: up (negative Fn)	1	4	1	3	73	68	15	171
	2	3	4	1	202	84	136	296
	3	4	4	0	224	72	122	278
	all	11	9	4	163	98	15	296
NORMAL: down (positive Fn)	1	3	1	4	81	26	53	106
	2	3	4	1	19	9	11	29
	3	2	4	2	74	76	20	127
	all	8	9	7	56	44	11	127
RESULTANT: (Fr)	1	7	1	0	108	72	27	201
	2	4	4	0	193	84	105	304
	3	4	4	0	248	53	173	286
	all	15	9	0	168	90	27	304

NOTE: See explanatory note following Table 3.4c.

Table 3.4b: Hand-on-rail trials: peak handrail forces - normalized values

FORCE COMPONENT (% of body weight)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	6	1	1	5.1	1.5	2.8	7.0
	2	4	4	0	9.1	4.6	2.5	13.1
	3	4	4	0	11.8	4.2	7.1	17.0
	all	14	9	1	8.2	4.3	2.5	17.0
M-L: to right (negative Fx)	1	3	1	4	2.9	1.8	1.7	5.0
	2	4	4	0	4.1	3.1	2.5	8.8
	3	4	4	0	4.8	1.6	3.6	7.2
	all	11	9	4	4.0	2.2	1.7	8.8
A-P: backward (negative Fy)	1	2	1	5	1.4	0.1	1.3	1.5
	2	2	4	2	4.1	1.7	2.9	5.4
	3	1	4	3	1.9	—	1.9	1.9
	all	5	9	10	2.6	1.7	1.3	5.4
A-P: forward (positive Fy)	1	7	1	0	7.3	3.5	4.1	14.5
	2	4	4	0	16.7	5.1	11.5	23.7
	3	4	4	0	24.1	1.4	22.6	26.1
	all	15	9	0	14.3	8.1	4.1	26.1
VERTICAL: up (negative Fz)	1	5	1	2	5.7	6.3	1.3	16.6
	2	3	4	1	18.9	9.3	11.0	29.2
	3	4	4	0	19.5	7.8	8.5	26.5
	all	12	9	3	13.6	9.8	1.3	29.2
VERTICAL: down (positive Fz)	1	7	1	0	8.8	8.1	1.3	21.6
	2	3	4	1	7.1	6.4	3.0	14.5
	3	4	4	0	11.3	11.5	3.4	28.3
	all	14	9	1	9.1	8.3	1.3	28.3
AXIAL: backward (negative Fa)	1	3	1	4	1.3	0.1	1.2	1.5
	2	2	4	2	4.0	1.2	3.2	4.8
	3	0	4	4	—	—	—	—
	all	5	9	10	2.4	1.6	1.2	4.8
AXIAL: forward (positive Fa)	1	7	1	0	9.5	6.1	4.5	19.5
	2	4	4	0	11.9	4.4	8.4	18.1
	3	4	4	0	14.4	4.5	9.0	19.6
	all	15	9	0	11.5	5.4	4.5	19.6
NORMAL: up (negative Fn)	1	4	1	3	9.4	8.2	2.6	21.2
	2	3	4	1	25.8	9.8	17.8	36.7
	3	4	4	0	30.3	6.4	21.5	35.6
	all	11	9	4	21.4	12.1	2.6	36.7
NORMAL: down (positive Fn)	1	3	1	4	9.5	2.5	7.0	12.1
	2	3	4	1	2.9	1.9	1.5	5.1
	3	2	4	2	12.5	14.1	2.5	22.4
	all	8	9	7	7.8	7.0	1.5	22.4
RESULTANT: (Fr)	1	7	1	0	13.5	7.6	4.8	22.9
	2	4	4	0	25.9	8.5	18.5	37.6
	3	4	4	0	33.8	2.9	30.5	37.0
	all	15	9	0	22.2	11.1	4.8	37.6

NOTE: See explanatory note following Table 3.4c.

Table 3.4c: Hand-on-rail trials: peak handrail forces - time of peak value

FORCE COMPONENT (timing in seconds)	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED invalid	EXCLUDED no-force	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
M-L: to left (positive Fx)	1	6	1	1	0.680	0.065	0.560	0.750
	2	4	4	0	0.735	0.205	0.505	0.965
	3	4	4	0	0.791	0.257	0.455	1.080
	all	14	9	1	0.728	0.170	0.455	1.080
M-L: to right (negative Fx)	1	3	1	4	0.905	0.468	0.365	1.180
	2	4	4	0	0.296	0.356	0.110	0.830
	3	4	4	0	0.405	0.193	0.250	0.660
	all	11	9	4	0.502	0.403	0.110	1.180
A-P: backward (negative Fy)	1	2	1	5	0.097	0.032	0.075	0.120
	2	2	4	2	0.097	0.018	0.085	0.110
	3	1	4	3	0.575	——	0.575	0.575
	all	5	9	10	0.193	0.214	0.075	0.575
A-P: forward (positive Fy)	1	7	1	0	0.698	0.320	0.410	1.305
	2	4	4	0	0.738	0.168	0.535	0.920
	3	4	4	0	0.798	0.237	0.510	1.090
	all	15	9	0	0.735	0.252	0.410	1.305
VERTICAL: up (negative Fz)	1	5	1	2	0.654	0.339	0.290	1.080
	2	3	4	1	0.788	0.211	0.560	0.975
	3	4	4	0	0.786	0.227	0.495	1.050
	all	12	9	3	0.732	0.262	0.290	1.080
VERTICAL: down (positive Fz)	1	7	1	0	0.526	0.301	0.225	1.170
	2	3	4	1	0.477	0.053	0.420	0.525
	3	4	4	0	0.368	0.106	0.280	0.500
	all	14	9	1	0.470	0.223	0.225	1.170
AXIAL: backward (negative Fa)	1	3	1	4	0.505	0.528	0.110	1.105
	2	2	4	2	0.255	0.247	0.080	0.430
	3	0	4	4	——	——	——	——
	all	5	9	10	0.405	0.417	0.080	1.105
AXIAL: forward (positive Fa)	1	7	1	0	0.610	0.257	0.420	1.170
	2	4	4	0	0.673	0.182	0.500	0.830
	3	4	4	0	0.730	0.456	0.350	1.345
	all	15	9	0	0.659	0.287	0.350	1.345
NORMAL: up (negative Fn)	1	4	1	3	0.805	0.124	0.685	0.975
	2	3	4	1	0.790	0.203	0.570	0.970
	3	4	4	0	0.793	0.229	0.505	1.065
	all	11	9	4	0.796	0.169	0.505	1.065
NORMAL: down (positive Fn)	1	3	1	4	0.720	0.390	0.485	1.170
	2	3	4	1	0.208	0.158	0.110	0.390
	3	2	4	2	0.400	0.163	0.285	0.515
	all	8	9	7	0.448	0.334	0.110	1.170
RESULTANT: (Fr)	1	7	1	0	0.755	0.246	0.490	1.170
	2	4	4	0	0.721	0.211	0.530	0.965
	3	4	4	0	0.796	0.237	0.500	1.080
	all	15	9	0	0.757	0.220	0.490	1.170

NOTE: Explanatory notes are provided on the following page.

Explanatory notes for Tables 3.2 to 3.4

1. The peak forces were determined by searching each data record, from the time of initial contact of the right hand with the handrail up to the point in time at which the motion of the body was estimated to have stopped (see Tables 3.5 to 3.7 for these timing data). In trials where the left hand contacted the handrail (approximately 15% of trials in the main experiment, 70% in the feet-obstructed trials, and 40% in the hand-on-rail trials), the search for the peak was terminated at the point where the left hand first touched the handrail.

2. The coordinate system used to define the components of the resultant force vector is defined in Figure 2.5. Note that the sagittal-plane component of the force is decomposed in two ways: 1) as horizontal (Fy) and vertical (Fz) components, and 2) as axial (Fz) and normal (Fn) components (the axial direction is along the longitudinal axis of the handrail, the normal direction is perpendicular to the longitudinal axis).

3. The "absolute forces" are presented in Newtons (4.45 N/lb) and the "normalized" forces are presented as a percentage of body weight. The timing of the peak forces were recorded relative to the onset of platform deceleration (i.e. the point in time when the deceleration jerk first exceeded 10 m/s^3).

4. For each variable, the descriptive statistics were calculated using the number of trials indicated as being "included". Trials were excluded from the calculation if the response was "invalid" (see Table 3.1) or if there was negligible force (i.e. < 10N) generated in that particular direction during the trial.

Table 3.5: Main experiment: kinematic and electromyographic data

VARIABLE	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Grip location: M-L (m)	1	40	8	-0.004	0.040	-0.074	0.061
	2	25	23	0.005	0.039	-0.060	0.067
	3	15	33	0.010	0.033	-0.048	0.052
	all	80	64	0.001	0.038	-0.074	0.067
Grip location: A-P (m)	1	40	8	0.263	0.054	0.158	0.381
	2	25	23	0.294	0.038	0.215	0.362
	3	15	33	0.318	0.057	0.212	0.424
	all	80	64	0.283	0.054	0.158	0.424
Grip location: vertical (m)	1	40	8	0.903	0.047	0.805	0.993
	2	25	23	0.878	0.035	0.801	0.940
	3	15	33	0.844	0.043	0.762	0.907
	all	80	64	0.884	0.048	0.762	0.993
Time of initial contact (s)	1	40	8	0.512	0.099	0.353	0.869
	2	25	23	0.437	0.057	0.324	0.546
	3	15	33	0.405	0.065	0.334	0.518
	all	80	64	0.468	0.093	0.324	0.869
Time of full grasp (s):	1	40	8	0.631	0.126	0.453	0.986
	2	25	23	0.564	0.082	0.358	0.729
	3	15	33	0.537	0.099	0.389	0.723
	all	80	64	0.593	0.115	0.358	0.986
Time of muscle activation (s)	1	40	8	0.217	0.085	0.087	0.590
	2	25	23	0.179	0.046	0.043	0.267
	3	15	33	0.138	0.039	0.054	0.206
	all	80	64	0.190	0.073	0.043	0.590
Time of step contact (s)	1	14	34	1.413	0.326	0.995	2.120
(if any)	2	21	27	0.899	0.190	0.685	1.590
	3	15	33	0.746	0.100	0.640	0.945
	all	50	94	0.997	0.345	0.640	2.120
Time to restabilize (s)	1	40	8	1.495	0.563	0.686	2.686
(estimated)	2	25	23	1.492	0.388	0.801	2.251
	3	15	33	1.508	0.283	1.118	2.151
	all	80	64	1.496	0.466	0.686	2.686
Maximum velocity: M-L (m/s)	1	38	10	0.266	0.211	0.024	0.775
(toward handrail)	2	24	24	0.403	0.211	0.070	0.859
	3	14	34	0.424	0.193	0.115	0.860
	all	76	68	0.338	0.218	0.024	0.860
Maximum velocity: A-P (m/s)	1	38	10	0.365	0.149	0.232	0.803
	2	24	24	0.658	0.130	0.461	0.860
	3	14	34	0.890	0.124	0.735	1.147
	all	76	68	0.554	0.248	0.232	1.147
Maximum velocity: vert (m/s)	1	38	10	0.557	0.511	0.056	1.469
	2	24	24	1.175	0.491	0.183	1.793
	3	14	34	1.353	0.457	0.649	1.951
	all	76	68	0.899	0.601	0.056	1.951

NOTE: See explanatory notes on the page following Table 3.7.

Table 3.6: Feet-obstructed trials: kinematic and electromyographic data

VARIABLE	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Grip location: M-L (m)	1	8	0	0.010	0.041	-0.043	0.057
	2	6	2	0.032	0.026	-0.011	0.066
	3	2	6	0.059	0.017	0.047	0.071
	all	16	8	0.024	0.037	-0.043	0.071
Grip location: A-P (m)	1	8	0	0.212	0.065	0.134	0.341
	2	6	2	0.220	0.052	0.139	0.284
	3	2	6	0.192	0.017	0.180	0.204
	all	16	8	0.212	0.055	0.134	0.341
Grip location: vertical (m)	1	8	0	0.940	0.055	0.839	1.010
	2	6	2	0.926	0.044	0.861	0.987
	3	2	6	0.906	0.013	0.896	0.915
	all	16	8	0.930	0.047	0.839	1.010
Time of initial contact (s)	1	8	0	0.545	0.076	0.464	0.686
	2	6	2	0.457	0.039	0.396	0.496
	3	2	6	0.376	0.035	0.351	0.401
	all	16	8	0.491	0.084	0.351	0.686
Time of full grasp (s):	1	8	0	0.685	0.106	0.564	0.836
	2	6	2	0.576	0.073	0.496	0.679
	3	2	6	0.476	0.106	0.401	0.551
	all	16	8	0.618	0.116	0.401	0.836
Time of muscle activation (s)	1	8	0	0.234	0.091	0.142	0.423
	2	6	2	0.212	0.122	0.082	0.444
	3	2	6	0.087	0.054	0.049	0.125
	all	16	8	0.208	0.106	0.049	0.444
Time of step contact (s)	1	0	8	———	———	———	———
(if any)	2	1	7	0.940	———	0.940	0.940
	3	0	8	———	———	———	———
	all	1	23	0.940	———	0.940	0.940
Time to restabilize (s)	1	8	0	1.535	0.827	0.936	3.386
(estimated)	2	6	2	1.699	0.542	1.246	2.729
	3	2	6	1.434	0.684	0.951	1.918
	all	16	8	1.584	0.676	0.936	3.386
Maximum velocity: M-L (m/s)	1	8	0	0.258	0.225	0.056	0.627
(toward handrail)	2	5	3	0.359	0.194	0.125	0.598
	3	2	6	0.414	0.113	0.334	0.494
	all	15	9	0.313	0.202	0.056	0.627
Maximum velocity: A-P (m/s)	1	8	0	0.296	0.064	0.221	0.436
	2	5	3	0.519	0.059	0.470	0.617
	3	2	6	0.752	0.005	0.749	0.756
	all	15	9	0.431	0.176	0.221	0.756
Maximum velocity: vert (m/s)	1	8	0	0.311	0.212	0.123	0.739
	2	5	3	0.736	0.390	0.275	1.274
	3	2	6	0.947	0.564	0.549	1.346
	all	15	9	0.537	0.395	0.123	1.346

NOTE: See explanatory notes on the page following Table 3.7.

Table 3.7: Hand-on-rail trials: kinematic and electromyographic data

VARIABLE	PERTURBATION MAGNITUDE	NUMBER OF TRIALS: INCLUDED	EXCLUDED	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Grip location: M-L (m)	1	7	1	0.002	0.015	-0.025	0.016
	2	4	4	0.001	0.013	-0.016	0.013
	3	4	4	0.008	0.008	-0.001	0.019
	all	15	9	0.004	0.012	-0.025	0.019
Grip location: A-P (m)	1	7	1	0.279	0.024	0.245	0.304
	2	4	4	0.263	0.027	0.238	0.302
	3	4	4	0.256	0.028	0.222	0.290
	all	15	9	0.269	0.026	0.222	0.304
Grip location: vertical (m)	1	7	1	0.894	0.029	0.868	0.943
	2	4	4	0.911	0.025	0.876	0.935
	3	4	4	0.905	0.019	0.880	0.927
	all	15	9	0.901	0.025	0.868	0.943
Time of muscle activation (s)	1	7	1	0.147	0.031	0.095	0.180
	2	4	4	0.131	0.009	0.120	0.141
	3	4	4	0.128	0.017	0.110	0.148
	all	15	9	0.138	0.024	0.095	0.180
Time of step contact (s)	1	0	8	———	———	———	———
(if any)	2	1	7	1.110	———	1.110	1.110
	3	4	4	1.155	0.670	0.530	2.070
	all	5	19	1.146	0.580	0.530	2.070
Time to restabilize (s)	1	7	1	1.158	0.434	0.653	1.864
(estimated)	2	4	4	1.189	0.384	0.741	1.679
	3	4	4	1.460	0.307	1.139	1.723
	all	15	9	1.247	0.388	0.653	1.864
Maximum velocity: M-L (m/s)	1	6	2	0.139	0.076	0.068	0.271
	2	4	4	0.448	0.215	0.166	0.633
	3	3	5	0.491	0.338	0.172	0.846
	all	13	11	0.315	0.249	0.068	0.846
Maximum velocity: A-P (m/s)	1	6	2	0.285	0.030	0.254	0.323
	2	4	4	0.532	0.050	0.480	0.596
	3	3	5	0.745	0.005	0.741	0.750
	all	13	11	0.467	0.196	0.254	0.750
Maximum velocity: vert (m/s)	1	6	2	0.097	0.039	0.043	0.139
	2	4	4	0.393	0.143	0.206	0.553
	3	3	5	0.540	0.108	0.468	0.664
	all	13	11	0.290	0.213	0.043	0.664

NOTE: See explanatory notes on the following page.

Explanatory notes for Tables 3.5 to 3.7

1. *Grip location* is recorded in terms of the coordinates of the reflective marker placed on the dorsal surface of the right wrist (at the base of the hand), measured at the time when the hand first achieved a full grip (see comment #3 below) on the handrail. The m-l (x) coordinate is measured relative to the center-line of the handrail; the positive direction is to the subject's right (i.e. toward the "wall" side of the handrail). The a-p (y) coordinate is measured relative to the backboard mounted at the rear of the top tread of the mock stairway (if the stairway included another step above the top tread, the backboard would lie in the plane of the riser). The vertical (z) coordinate is measured relative to the top surface of the top tread.

2. All timing measures were recorded relative to the onset of platform deceleration (defined as the point in time when the deceleration jerk first exceeded 10 m/s^3).

3. *Time of initial contact* represents the time when the right hand first contacted the handrail, as estimated from the video recordings. *Time of full grasp* represents the time at which the fingers and thumb first achieved maximum flexion, in grasping the handrail. These parameters are not presented for the hand-on-rail trials, because the subject grasped the handrail prior to the start of these trials.

4. *Time of muscle activation* represents the time of onset (latency) of the earliest activation (EMG) occurring in the muscles of the right arm. For the main-experiment and feet-obstructed trials, the shoulder abductor (deltoid) was the first muscle to be activated; for the hand-on-rail trials, the finger/wrist extensors (extensor digitorum) tended to be activated first (typically, the deltoid was largely inactive during these trials). The EMG latencies were determined through visual inspection of the plotted signals (i.e. by moving a cursor on the computer monitor).

5. *Time of step contact* represents the time at which the swing foot first contacted the bottom tread of the mock stairway, in trials where the subject stepped. This was recorded by means of the timing switches that were mounted underneath the tread.

6. *Time to restabilize* is an estimate of the time that was required for the motion of the body to be completely arrested. This was estimated from inspection of the video recordings. Where feasible, the estimates were checked by comparing them to the velocity of the reflective marker placed on the sternum of the subject's body; however, in many trials, it was not possible to digitize this marker up to the time of zero velocity, because the motion of the body often tended to block the camera views in the late stages of the response.

7. *Maximum velocity* is the maximum absolute velocity, in the a-p (forward), m-l (to the subject's right, i.e. toward the handrail) and vertical (downward) directions, of the reflective marker placed on the sternum of the subject's body. Note that there was negligible velocity in the backward or upward directions, and that the leftward m-l velocity (away from the handrail) was, on average, 2-5 times smaller than the rightward m-l velocity (toward the handrail). Obstruction of the sternal marker, due to the displacement of the body, prevented determination of the maximum velocity in a small number of the trials (n=4 for the main experiment, n=1 for the feet-obstructed trials, n=2 for the hand-on-rail trials).

4. DISCUSSION

The results of this pilot study are discussed below, with regard to: 1) the biomechanics of the grasping responses that were observed, 2) potential practical implications for the design of handrails, and 3) the strengths and limitations of the methodology that was developed. It is important to keep in mind that the points raised in Sections 4.1 and 4.2 are specific to the experimental simulation that was studied. The degree to which these results may generalize to prevention of falls during actual stairway use cannot be verified directly, because of the paucity of data regarding "real" stairway falls. Based on available information, the experimental protocol does appear to simulate a number of features of stairway loss of balance; however, there are also several potentially significant limitations. In particular, it is possible that the subjects' prior awareness of the nature of the test, and the absence of downward body motion at perturbation onset, acted to facilitate accurate and rapid grasping responses. These potential limitations are discussed in detail in Section 4.3. Supplementary experiments to assess possible effects on the handrail demands are also proposed in this section.

4.1 Biomechanical issues

A fundamental question, unanswered prior to performing this study, was whether it is possible to generate a handrail grasping response with sufficient speed and accuracy to prevent a fall after losing balance on a stairway. The results from the experimental simulation showed that it is possible to generate a grasping response, and sizeable stabilizing handrail force, very quickly in response to a postural disturbance. Furthermore, these stabilizing responses were clearly of functional significance, resulting in a marked reduction in the incidence of "falls" (i.e. contact with the crash pad), compared to trials where the handrail was absent.

The speed of the observed grasping responses was quite remarkable. Typically, the earliest muscle activation in the arms began within 0.2 seconds of the onset of the postural perturbation, initial contact with the handrail occurred within 0.5 seconds, and a full grasp of the handrail was achieved within 0.6 seconds. On average, the peak in the resultant stabilizing force was reached within 0.9 seconds. Although our earlier work has also demonstrated very rapid activation and movement of the arm in response to postural perturbation[12,13], the work described here is apparently the first to examine the timing of the grasp itself and the grasping forces generated.

The accuracy of the arm movements was also remarkable. There were no trials where the hand missed the handrail completely, and very few trials where the initial contact did not result in a functional grip. This accuracy was achieved, even in the earliest (unpractised) trials, despite the fact that the perturbations were unpredictable in terms of time of onset and magnitude. Furthermore, subjects were given instructions that discouraged looking at the handrail prior to the onset of the perturbation, and, although head and eye movements were not analyzed, it appeared that the subjects seldom looked directly at the handrail during the grasping response.

The handrail forces that were generated were substantial. On average, the resultant force peaks were approximately 250N (60lb) and 300N (70lb), for the medium and large perturbations, respectively, and the resultant force in individual trials ranged as high as 540N (120lb). At the medium perturbation, which induced center-of-mass movement typical of an average stairway gait (0.5m/s)[15], the average peak forces in the m-l (to the subject's left), a-p (forward) and vertical (downward) directions were 150N, 160N and 130N, respectively. These force components were approximately 15-20% of body weight. In our previous studies[1-5], where we performed static measurements of the ability to generate forces on a stairway handrail, the average capabilities of young-adult subjects were found to be about 20% and 40% of body weight, in the forward and downward directions, respectively. In healthy older adults, aged 60 and older, the average capabilities were approximately half of these values. Thus, it would appear that the force demands measured in the current study did not differ greatly from the static force-generating capabilities measured in our previous studies, particularly in older adults.

Caution must be exercised, however, in attempting to compare the results of static and dynamic force measurements, as the ability to generate force under dynamic conditions, particularly when the response is a reflex-like "automatic" reaction, may well exceed static measurements of volitional effort. In addition, the positioning of the arm, relative to the body, was substantially different in the current dynamic grasping experiments, in comparison to the postures adopted during the previous static experiments (those experiments were not intended to simulate the situation where the hand must grab for the handrail). In particular, because of the motion of the body that occurred during the time required to grasp the rail, the hand tended to be located posterior to the shoulder and trunk by the time that the peak forces were generated, whereas the hand tended to have a more anterior position in the previous study. As a result of the trunk and shoulder motion occurring in the dynamic situation, it would appear that the force generation often tended to involve a pulling, rather than pushing, action. Furthermore, the falling body, in "pulling" on the arm, will tend to induce a reaction force on the handrail even in the absence of active effort to generate handrail force, provided that the hand remains anchored on the rail. In other words, the passive stiffness of the limb can contribute to the generation of the stabilizing handrail force. It should be emphasized that the discussion above does not necessarily pertain to the situation where the subject is already contacting the handrail when loss of balance occurs. As can be seen by comparing Figures 3.1 and 3.4, there appears to be much less anterior motion of the shoulder, relative to the hand, when the hand is contacting the handrail at onset of perturbation. The previous static experiments may have provided a reasonable approximation of the arm postures that occur in this situation.

4.2 Practical issues

The present results support the functional significance of the handrail grab response in the maintenance of postural stability during stairway descent. Given the fact that stairway users frequently fail to hold or touch the handrail, it is therefore imperative that handrails be designed to meet the biomechanical demands of the grabbing response. At the same time, however, it is also important to ensure that the handrail design also meets the biomechanical demands that are specific to the hand-on-rail response, where the stairway user is contacting the handrail when loss of balance occurs. As discussed in the next section, there do, in fact, appear to be some differences in the biomechanical demands associated with the grab and hand-on-rail responses. For example, the hand is more likely to pull up on the rail, with greater force, during the hand-on-rail condition, and this may have implications for handrail design, i.e. the need to provide a finger purchase that will allow adequate "pull-up" force to be generated without slippage.

Although the present findings are based on a very limited sample of subjects, they do suggest some factors that may be of importance in designing handrails and setting building code requirements. Although a discussion of these factors is presented below, it should be emphasized that further research, involving a larger number and wider range of subjects, is necessary to confirm these very preliminary results.

One observation that may have implications for handrail design relates to the trajectory at which the hand approaches the handrail. The results showed this to be dependent on the lateral displacement of the body from the handrail. When the subject is distant from the rail, the hand tends to move in a more horizontal plane, and initial contact tends to occur with the extended thumb "hooking" onto the inside edge of the handrail and/or the fingers wrapping around the outside of the rail. Conversely, when the subject is standing close to the handrail, the hand tends to move in a more curved trajectory, up and over the rail, so that the "angle of attack" is more nearly vertical, and initial contact tends to occur in the "notch" between the thumb and index finger. With a handrail that is circular in cross-section, the angle of attack is not critical in determining whether an adequate grip can be achieved. The angle of attack may, however, be more important for handrails having edges or more complex shapes. It is not known whether the central nervous system (CNS) will automatically tailor the trajectory to suit the shape of the handrail, or whether any such alterations in the path, or timing, of the trajectory will compromise the ability to achieve a functional grip. Conversely, it is possible that edges on the railing may actually facilitate the ability to "hook" onto the handrail with the thumb or fingers. Further research is needed to examine these issues.

The ability to generate the handrail forces needed to stabilize the body depends, of course, on the ability to maintain the grip on the rail. In the present study, there was only one trial where the subject actually "lost" his grip; however, it is important to remember that the handrail used in the study was circular in cross-section and had a matte finish, properties that might be considered to be optimal[3,5,24]. Further research is needed to determine whether other handrail shapes and surface textures will be less (or possibly more) effective in allowing the grip to be maintained. With regard to the size of the handrail, the railing used in this study was 50mm (2in) in diameter, a size which lies near the upper end of the range allowed by many building codes. The recommended diameter, based on our previous static experiments[3], was 38mm (1.5in). The relatively large size of the handrail used here did not appear to create any difficulties for the subjects tested in this study; however, it is important to note that all of the subjects had near-average or above-average hand size[25] and all had substantial grip strength (subject #4, in fact, had an abnormally strong grip). Further research is needed to determine whether this size of handrail is appropriate for subjects with smaller hands and lower levels of grip strength, as well as subjects with disability of the hand (e.g. arthritis). It would also be very useful for designers to know whether handrails of different size, or shape, would actually optimize, over a wide range of subject characteristics, the ability to achieve an adequate handrail grip.

Although the influence of handrail height was not studied explicitly, it seems apparent, in observing the responses of the subjects, that the height of the handrail will have a profound impact on the biomechanical demands placed on the handrail grip, and may well play a crucial role in determining whether attempts to use the handrail will actually help to prevent a fall. Handrail height is expected to influence the biomechanical demands in two ways, by affecting: 1) the location of the grip, relative to the body, and 2) the time required to achieve this grip. The grip location, particularly the a-p location, is critical in defining the demands placed on the handrail: if the grip is posterior to the body, then a pulling action will ensue, whereas an anterior placement will lead to a pushing action, as discussed earlier. Furthermore, the height of the grip is critical in determining the stabilizing moments that the handrail force generates with respect to the feet. As discussed in our earlier papers[1-5], a higher handrail will allow a given handrail force to generate a larger stabilizing moment about the foot axis; hence, the level of handrail force needed to stabilize the body may well decrease as the height is raised. With regard to timing, stability may be jeopardized if the generation of stabilizing forces is delayed due to an increase in time required to contact the handrail. We have already performed a small number of pilot tests to examine this issue, and the results suggest that the low heights, such as 76cm (30in), that are allowed by many building codes may be particularly dangerous in this regard. In fact, the pilot subjects appeared, in some trials, to experience a great deal of difficulty in just reaching the handrail, much less generating adequate stabilizing force. It should be noted that the height of 86cm (34in) that was tested in the present study lies near the upper limits of many building codes, but is still lower than the height recommendation (91cm or 36in) based on our previous static handrail studies[1,2,4,5].

4.3 Methodological issues

The pilot tests were very useful in identifying a number of specific ways in which the protocol could be improved, in future studies. One problem that was identified pertained to the large number of "invalid" responses. The largest group of these involved either stepping on, or pushing against, the tread cover (the intended purpose of the tread cover was to force the foot to land on the bottom tread, so as to simulate an overstep). This strategy occurred primarily in two of the four subjects, and appeared to be related to the type of shoe sole: these subjects wore shoes with high-friction soles that prevented the foot from slipping off the tread cover. This problem could be solved very easily, in future studies, by placing a low-friction cover (e.g. nylon) over the soles of the shoes. Another response that invalidated the measurements, albeit in a very small number of trials, involved grasping the protective wall of the moving platform with the left arm. A small modification to the platform configuration would readily solve this problem. Finally, one subject showed a tendency, on occasion, to step onto the top of the crash pad. The foam barrier (see Figure 2.1) was placed on top of the crash pad for the express purpose of discouraging this type of response, and did appear to be effective in doing so in the vast majority of the trials.

In terms of reducing testing and analysis time and costs, it would appear that the number of experimental trials could be cut in half simply by using only one stance-leg condition, since the statistical analyses indicated that the initial stance leg (left or right) had little or no effect on the force generation, grip location or timing of the grasp. It may also be possible to reduce the number of repeated trials ("rounds), particularly since the earliest responses are least likely to be contaminated by practice effects. It does, however, appear to be important to retain the other task conditions. Variation in perturbation magnitude is essential to maintaining unpredictability, as discussed below, and variation in lateral stance position was found to have some interesting and potentially important effects on the trajectory of the hand.

The small series of hand-on-rail trials was included in the protocol to simulate the condition where the subject is touching the handrail when loss of balance occurs. Although, in general, the hand-on-rail task resulted in mean force levels that were either less than, or approximately equal to, the forces recorded during the main experiment, the two variables related to pulling up on the rail (upward normal force and upward vertical force) actually showed higher force levels during the hand-on-rail task, in comparison to the main-experiment trials. In view of these differences, and the implications for handrail design (e.g. the importance of providing a purchase for the fingers to pull up against), it would seem prudent to continue to test the hand-on-rail condition in future experiments.

The feet-obstructed trials were included in the protocol in order to explore the possibility of using a small foot obstruction as a means of discouraging the subjects from stepping. By encouraging the subjects to rely entirely on the handrail, we hoped to place an upper limit on the handrail forces. In actuality, the results showed little evidence of higher force during these trials. The only increase in force, relative to the main experiment, was seen in the upward force components; however, similarly high levels of upward force were also recorded during the hand-on-rail task. Hence, if the latter task is included in the protocol, there seems to be little reason to also include the feet-obstructed task condition, in future experiments.

A more fundamental question remains to be addressed: does the experimental approach that we have developed adequately simulate the biomechanics of handrail use during stairway loss of balance? Our approach does achieve this goal in a number of respects: 1) the relative motion, between the upper body and the staircase, achieves a velocity and momentum that is typical of stairway gait; 2) the leading foot is forced to miss the next stair tread and to land on the step below, as might occur in the event of an overstep; and 3) the arm muscles are activated at latencies that are typical of rapid, reflex-like postural reactions, rather than volitional movement.

In designing the protocol, we addressed two additional concerns, associated with the possibility that subjects might respond in an anticipatory (predictive) manner, or might learn to perform more effectively with repeated exposure to the testing situation. Either type of adaptation would tend to compromise the simulation of "real-life" balance recovery, where events tend to happen unpredictably and without opportunity to practice one's response. Although subjects did, in fact, show evidence of anticipatory arm-muscle activation in a small percentage of trials (14%, over all conditions tested), we were well able to detect and exclude these responses by monitoring arm EMGs. It is also worth noting that the vast majority of these anticipatory responses occurred at the largest perturbation. Once the platform has moved past the position associated with the medium perturbation, it can be deduced that the perturbation is going to involve the largest magnitude. Apparently, the CNS was, in some instances, able to take advantage of this predictable feature to generate anticipatory responses. Focusing the analysis on the medium magnitudes, or inclusion of additional perturbation magnitudes and/or waveforms in order to "confuse" the CNS, will help to eliminate this problem in future studies.

It appears that the performance of the mental-arithmetic task during each trial was an important factor in preventing subjects from preplanning a "volitional" movement. Anecdotally, subjects reported that this secondary task was very effective in distracting them, and they perceived that it noticeably altered their pattern of response. In addition, the instructions to try not to step (and the inclusion of small perturbations that made it possible to achieve this instruction, at least some of the time) was likely an important factor in preventing preplanning of "volitional" stepping. The fact that a sizeable proportion of trials were completed without stepping clearly indicates that subjects did not simply preplan to step in every trial.

As for "learning" or "practice" effects associated with repeated exposure to the perturbations, the statistical analyses actually failed to show any evidence of systematic changes in force generation, grip location or timing of the grasping response. However, it should be noted that the small sample size in this pilot study limits the statistical power of the analyses, and it is possible that relatively small systematic trends were not detected. In fact, trial-to-trial variability in response tended to be quite large, and this may have acted to mask underlying learning effects. As mentioned earlier, future studies would likely benefit by minimizing the number of repeated trials, and focusing, where possible on the earliest trials.

Although the protocol appeared to be effective in minimizing any tendency to preplan "volitional" grasping or stepping movements, it must be acknowledged that the subjects did have the opportunity to survey their surroundings, i.e. with respect to the location of the handrail, and that this could have facilitated the ability to generate an accurate and rapid grasping response. However, it is also possible that the same phenomenon occurs automatically in daily life, i.e. it may be that the CNS maintains and continuously updates an internal representation of the environment and automatically uses this information in generating accurate and rapid compensatory reactions. This is supported by our recent studies, which have demonstrated that even the earliest arm motion evoked by postural perturbation is directed toward the nearest potential "handholds" in the environment, even when subjects are naive, have had no prior exposure to the perturbation and the handholds are not in close proximity (i.e. 1m away)[12,13].

It must also be acknowledged that, even though the exact timing of the perturbation was unpredictable, subjects were always well aware that a perturbation was going to occur, and it is possible that this expectation could have helped to potentiate a more rapid response. In opposition to this view, however, is evidence that very rapid arm reactions persist, over large numbers of repeated trials, even when the subject has had ample opportunity to become aware that the perturbation does not pose a significant threat to stability[12]. This latter finding suggests a degree of automaticity that may be largely independent of the expectations of the subject. Concerns that subject expectation affects the response could, in theory, be addressed directly by studying responses to perturbations that are truly unexpected; however, this is a not feasible option, in our institution, because the potential risk of injury, and associated ethical considerations, require that the subject be informed as to the nature of the experiment. The best that can be achieved is to make the perturbation onset as unpredictable as possible. One possible approach is to embed the larger perturbation that is of interest within a long sequence of trials involving very small perturbations, so as to catch the subject "off guard". Of course, this approach can only provide a limited amount of useful data. In fact, the first large-perturbation trial may be the only trial that simulates the response to unexpected perturbation, since the subject's expectations will change after experiencing that trial.

From a biomechanical perspective, a potential limitation pertains to the relative timing of the body motion and the initiation of the arm response. It is clear that the arm muscles are activated in response to onset of platform deceleration, at which point in time the extended leg is positioned over the tread cover (i.e. where the next stair tread would normally be located). For an overstep occurring during actual stairway gait, however, one would expect the first sensory indication of impending loss of balance to be associated with the failure to plant the leading foot on the stair tread, i.e. the stabilizing reaction would be triggered around the time at which the leading foot has dropped to the level of the next stair tread. The posture that would occur at onset of overstep, in a "real" stairway incident, is achieved (approximately) in the experimental trials, but it occurs after the onset of the platform perturbation. Filmed recordings of normal stairway gait[26] would suggest that the initial stance position that we used is, in fact, a reasonable approximation of the posture that occurs approximately 40ms earlier in the stairway gait cycle, relative to the point at which an overstep would occur. It is, at present, unclear whether this small discrepancy in timing would have a large effect on the biomechanics of the handrail use. Certainly, in a "real" overstep, the knee of the supporting leg will be flexed, rather than extended, at the onset of the grasping response, and the body will have dropped vertically relative to the supporting foot. However, because of the downward pitch of the handrail, the position of the trunk, shoulder and hand relative to the handrail, at the onset of the grasping response, may tend to be similar for both "real" oversteps and the experimental simulations, despite the postural differences noted; hence, the grasping trajectory may also be similar. Further experiments are need to examine this issue.

One might argue that the erect initial posture used in the testing protocol actually provides a better simulation of a loss of balance arising from catching the heel of the swing foot on the nosing of the supporting tread, rather than an overstep. This may well be true, in terms of the timing of the grasp-response initiation; however, the present protocol, in forcing the foot to miss the next tread, may fail to simulate accurately the added support that the swing foot could provide potentially in a "real" heel-catching incident, in the case where the foot slips down onto the next tread. On the other hand, the feet-obstructed test condition may simulate heel-catching incidents where the swing foot cannot be planted securely. Catching the heel is believed to be a relatively common precipitant of loss of balance during stairway descent[9], and this scenario may well be worthy of further investigation, although it does seem likely that any ability to plant the leading foot on the next tread will lead to handrail forces that are smaller than those required to recover from oversteps. Future experiments could investigate this by allowing subjects to step onto the next tread, i.e. by removing the tread cover currently used to force overstepping of this tread.

Another potential limitation pertains to the fact that the experimental approach does not simulate the downward center-of-mass velocity that would occur prior to perturbation during actual stairway gait. Instead, the vertical component of the body motion is induced entirely by the gravitational acceleration that occurs after perturbation onset, as the center of mass moves forward of the supporting foot. However, as indicated in Table 3.5, this did result in substantial downward trunk velocity, which was typically two to three times larger than the average downward velocity associated with unperturbed stairway gait (e.g. 1-1.5m/s versus 0.5m/s). Further perturbation experiments in which volitional gait movement is simulated, as described below, could determine whether the volitional motion has a significant effect on the handrail forces that are required to restore equilibrium.

In an actual overstep, it is quite possible that the ability to generate stabilizing reaction forces and torques with the leading foot, after it contacts the next tread, will be compromised, depending on the landing position of the leg and foot and the muscle activation that occurs. In the experimental protocol, we attempted to allow for the worst-case scenario, where <u>no</u> significant force is generated by the leading foot, by measuring the handrail forces that occurred when subjects did not step. The feet-obstructed trials were included in order to consistently prevent stepping at the higher perturbation magnitudes. This approach was, in fact, successful in increasing the proportion of non-stepping responses (the effect may have been largely psychological, since the actual level of physical constraint was small, i.e. subjects were well capable of stepping over, or through, the small foam-rubber barrier that was used). Although one might argue that the ability to avoid stepping was enhanced because the subjects were allowed to stand on both feet during this task condition, the reality is that the same a-p ankle torque can be generated with one leg <u>or</u> two. During stance, the maximum a-p ankle torque is limited typically, not by muscle strength, but by the size of the base of support; as the level of plantar-flexor torque is increased, the center of pressure will move to the front end of the foot, and attempts to generate further plantarflexor torque will cause the heels to rise off the floor[27].

From a motor-control perspective, potential limitations arise from the uncertainty about the specific sensory sources (i.e. vestibular, pressoceptive, proprioceptive or visual) that are used to drive the stabilizing response. It is quite possible that different sensory systems are used to trigger the responses to "real-life" oversteps, in comparison to the experimentally-induced loss of balance; however, in practice, this is unlikely to have a major influence on the biomechanics of the response. Numerous studies suggest that there is a great deal of redundancy in the posture control mechanisms, and that the CNS is quite able to use a wide range of differing sensory information, with nearly equal effectiveness, to drive the stabilizing postural reactions (at least in normal healthy subjects)[28]. Another potential limitation relates to the fact that the ongoing movement of the limbs, and associated sensory drive, that occurs during stairway gait is not simulated in the experimental approach. Previous studies suggest that the ability to generate stabilizing postural responses may, in fact, tend to be compromised by ongoing "volitional" movement[29]. If this is the case, then the results derived from the current approach may represent an upper limit on the performance of the postural control mechanisms.

The potential limitation pertaining to the absence of volitional movement could be evaluated, using the existing apparatus, by performing an experiment in which the platform is triggered to accelerate backward, after a preset interval (e.g. 200ms), shortly <u>after</u> a volitional step is initiated. The backward acceleration would cause the subject to pitch forward, as in the current protocol; however, in this case, the perturbation would be delivered during the course of ongoing volitional movement. Such a protocol could also serve to examine the effects of other potential limitations of the current approach described earlier, i.e. by better simulating the body posture and motion that would occur at the onset of a "real" overstep.

Nothwithstanding the fact that there are limitations, we believe that the testing approach developed and tested in the present study does provide an adequate simulation of the biomechanical factors that are most likely to affect the handrail demands, and that the potential limitations described above are unlikely to have a major impact. Supplementary pilot experiments could be performed to confirm whether this is the case, using the experimental approaches outlined above to determine whether subject expectation or pre-perturbation volitional movement has a significant effect on the timing, magnitude or direction of the handrail forces or the trajectory of the hand movement. Ultimately, of course, the exact degree to which any experimental approach mimics the biomechanics of "real" stairway accidents, and the use of handrails to recover balance, can only be determined by comparison to data collected during actual, truly unexpected stairway loss of balance. As discussed earlier, ethical and safety concerns limit the degree to which this is feasible in the laboratory, although it may be possible to collect a limited amount of data under carefully controlled conditions. Another possibility is to record actual naturally-occurring stairway fall and near-fall events; however, it should be cautioned that recording even a small number of accidents can be a rather expensive undertaking. In previous attempts to use this approach[30,31], the investigators were able to detect a total of only 12 stairway incidents, after manually scanning video recordings of over 32,000 stairway traverses. More recent developments in video technology, motion detectors and pattern-recognition software might allow for a semi-automated system that would make this approach a somewhat less labor-intensive, and costly, option. By using multiple cameras, with suitably selected fields of view, it may prove feasible to derive quantitative kinematic data from the recordings, which could then be compared to the experimentally-derived data.

5. LIST OF REFERENCES

1. Maki BE, Bartlett SA, Fernie GR. Effect of stairway pitch on optimal handrail height. *Human Factors* 1985; 27: 355-9.

2. Maki BE, Bartlett SA, Fernie GR. Influence of stairway handrail height on the ability to generate stabilizing forces and moments. *Human Factors* 1984; 26: 705-14.

3. Maki BE. Influence of handrail shape, size and surface texture on the ability of young and elderly users to generate stabilizing forces and moments. Technical report #29401 (prepared under contract #OSX84-00197), National Research Council of Canada. 1985.

4. Maki BE. Influence of handrail height and stairway slope on the ability of young and elderly users to generate stabilizing forces and moments. Technical report #29400 (prepared under contract #OSX83-00175), National Reseach Council of Canada. 1984.

5. Maki BE, Fernie GR. Biomechanical assessment of handrail parameters, with special consideration to the needs of elderly users. Technical report #29399 (prepared under contract #OSX82-00180), National Reseach Council of Canada. 1983.

6. Templer JA. The forgiving stair. In: Proceedings of the Human Factors Society, 28th Annual Meeting. 1984: 58-62.

7. Templer JA. The unforgiving stair. In: Proceedings of the International Conference on Building Use and Safety, Los Angeles. 1985: 122-6.

8. Templer JA, Hyde D. Towards the empathetic stair: a report of work in progress. In: Proceedings of ICAART 88. Montreal: 1988: 644-5.

9. Templer JA. The Staircase: Studies of hazards, falls and safer design. Cambridge, MA: The MIT Press, 1992.

10. Horak FB, Diener HC, Nashner LM. Influence of central set on human postural responses. *J Neurophysiol* 1989; 62: 841-53.

11. Maki BE, McIlroy WE, Perry SD. Influence of lateral destabilization on compensatory stepping responses. *J Biomech* 1996; 29: 343-53.

12. McIlroy WE, Maki BE. Early activation of arm muscles follows external perturbations of upright stance. *Neurosci Lett* 1995; 184: 177-80.

13. McIlroy WE, Maki BE. Compensatory arm movements evoked by transient perturbations of upright stance. In: Taguchi K et al, eds. Vestibular and Neural Front. Amsterdam: Elsevier, 1994: 489-92.

14. Peak Performance Technologies Inc. Peak Performance Technologies Inc.: Video and analog motion measurement systems: User's Guide. Englewood, CO: 1993.

15. Townsend MA, Lainhart SP, Shiavi R, Caylor J. Variability and biomechanics of synergy patterns of some lower-limb muscles during ascending and descending stairs and level walking. *Medical and Biological Engineering and Computing* 1978; 16: 681-8.

16. Pauls J. Are functional handrails within our grasp? *Building Standards* 1991; January/February: 6-12.

17. Pauls J. Are functional handrails within our reach and our grasp? *Southern building* 1989; September/October: 20-30.

18. Pauls J. Review of stair-safety research with the emphasis on Canadian studies. *Ergonomics* 1985; 28: 999-1010.

19. Park E, Meek SG. Adaptive filtering of the electromyographic signal for prosthetic control and force estimation. *IEEE Transactions on Biomedical Engineering* 1995; 42: 1048-52.

20. Neter J, Wasserman W, Kutner MH. Applied linear statistical models. Homewood, IL: Richard D. Irwin, 1985.

21. Montgomery DC. Design and analysis of experiments. Toronto, Canada: John Wiley and Sons, 1984.

22. Conover WJ, Iman RL. Rank transformations as a bridge between parametric and nonparametric statistics. *American Statistician* 1981; 35: 124-33.

23. McIlroy WE, Maki BE. Task constraints on foot movement and the incidence of compensatory stepping following perturbation of upright stance. *Brain Res* 1993; 616: 30-8.

24. Armstrong T, Chaffin DB, Miodonski R, Strobbe T, Boydstuw L. An ergonomic basis for recommendations pertaining to specific sections of OSHA standard 29 CFR part 1910 subpart D--walking and working surfaces. U.S. Department of Labor, Occupational Safety and Health Administration, Washington, DC. 1978.

25. Garrett JW. The adult human hand: Some anthropometric and biomechanical considerations. *Human Factors* 1971; 13: 117-31.

26. Joseph J, Watson R. Telemetering electromyography of muscles used in walking up and down stairs. *The Journal of Bone and Joint Surgery* 1967; 49B: 774-80.

27. Maki BE, Holliday PJ, Fernie GR. A posture control model and balance test for the prediction of relative postural stability. *IEEE Trans Biomed Eng* 1987; BME-34: 797-810.

28. Nashner LM. Analysis of stance posture in humans. In: Towe AL and Lushei ES, eds. Handbook of Behavioral Neurobiology (Volume 5, Motor Coordination). New York: Plenum Press, 1981; 527-565.

29. Stelmach GE, Phillips J, DiFabio RP, Teasdale N. Age, functional postural reflexes, and voluntary sway. *J Gerontol* 1989; 44: B100-106.

30. Templer JA, Mullet G, Archea JC. An analysis of the behavior of stair users. NBSIR 78-1554, National Bureau of Standards. 1978.

31. Archea JC, Collins BL, Stahl FI. Guidelines for stair safety. NBS-BSS 120, National Bureau of Standards, Washington, DC. 1979.

APPENDIX A - DETAILS OF PROTOCOL

Demonstration and preamble

The purpose of this study is to understand how people use handrails when they lose their balance on a stairway. We are going to simulate this by asking you to stand at the top of this small stairway, beside this handrail. The stairway has three steps, but the second step has been covered, so as to prevent you from stepping onto it.

We're going to do a number of trials. In each trial, the platform will begin to move gradually, it will gradually accelerate (pick up speed) for a few seconds and then it will stop suddenly, which will cause you to pitch forward, as if you'd lost your balance while you were walking down the stairs. The point at which the platform stops will be varied at random, so that you can't predict where or when it's going to stop. To distract you from thinking about the test, I'm going to ask you to count backward by 7's, out loud, as fast as possible, during each trial. Keep counting until the platform stops moving.

At the start of each trial, I will ask you to stand with your heels together, touching the backboard, and your feet centered on either this line ("far" position) or this line ("close" position). Stand straight, with your back against the backboard and look straight ahead at the "X". Hold your arms relaxed at your sides; your fingers should be extended and relaxed. Then, I will ask you to shift your weight onto one foot, and to move the other foot forward, so that the heel rests lightly against the edge of the tread. It's very important that you try to hold this position while the platform is accelerating. You won't actually lose your balance until the platform stops.

PRELIMINARY TESTS

T1	Weight measurement (spontaneous sway, standing on two AMTI's)
T2	EMG check

1. HANDRAIL TRIALS

<u>1.1 Unconstrained (familiarization) trials: 3 trials</u>

T3	magnitude:	*medium*
	position:	*close*
	stance foot:	*right*
	instruction:	*There are no specific instructions for this trial - do whatever comes naturally to keep your balance. Remember, though, to hold your foot in front and keep your arms at your sides while the platform is accelerating, and to count backward by 7's as fast as possible, starting at xx*.*
T4	magnitude:	*large*
T5	magnitude:	*small*

* NOTE: in all trials, select the starting number for the serial 7's as: test number + 100

1.2 Main-experiment trials: 3 rounds of 12 trials (randomized)

T6-T41	magnitude:	*small, medium, large*
	position:	*close, far*
	stance foot:	*right, left*
	instruction:	*Try to keep your balance by grabbing the handrail. Try not to step unless it is necessary. Remember to hold your foot in front and keep your arms at your sides while the platform is accelerating. Count backward by 7's as fast as possible, starting at xx.*

NOTE: have the subject step off the platform, and take a 5-minute seated rest, after each of the 3 rounds; restart the program and reinitialize the force plates at this time.

1.3 Obstructed-foot trials: 1 round of 6 trials (randomized)

T42-T47	magnitude:	*small, medium, large*
	position:	*close, far*
	stance foot:	*both (obstructed)*
	instruction:	*Try to keep your balance by only grabbing the handrail. Do not step. Remember to keep your arms at your sides while the platform is accelerating. Count backward by 7's as fast as possible, starting at xx.*

1.4 Hand-on-rail trials: 1 round of 6 trials (randomized)

T48-T53	magnitude:	*small, medium, large*
	position:	*close*
	stance foot:	*left, right*
	instruction:	*Place your hand on the handrail in a comfortable position. Try to choose the position that you would use if you were walking down a stairway. Hold onto the railing firmly, but do not push or pull on the rail until you start to lose your balance. Do not step. Remember to hold your foot in front and keep your left arm at your side while the platform is accelerating. Count backward by 7's as fast as possible, starting at xx.*

NOTE: Mark the hand position selected prior to the initial trial in this round, and use the same position in all subsequent trials.

2. CALIBRATION TRIALS

2.1 Hold-backboard trials: 1 round of 3 trials

T54-T56 magnitude: *small, medium, large* (test in ascending order)
position: *close*
stance foot: *right*
instruction: *We need to do three trials to calibrate the measurement system. Please stand in the near position and face the backboard. Hold onto the backboard, with your hands at waist level. Try not to move during the test. The platform will move the same way that it did before.*

NOTE: Have the subject step off the platform, and take a 5-minute seated rest, after completing these tests; REMOVE THE HANDRAIL, restart the program and reinitialize the force plates at this time.

3. NO-HANDRAIL TRIALS

3.1 No-handrail trials: 1 round of 6 trials (randomized)

T57-T62 magnitude: *small, medium, large*
position: *close*
stance foot: *right, left*
instruction: *Try to keep your balance without stepping, if possible. Do not grab anything. Remember to hold your foot in front and keep your arms at your sides while the platform is accelerating. Count backward by 7's as fast as possible, starting at xx.*