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Abstract

A two-part study was undertaken to investigate the effects of movement experiences on lower extremity function during impact activities. Group and single-subject performances were evaluated for a total of 12 male volunteers during landing (Study I) and running (Study II) activities. Standard biomechanical techniques were used to obtain kinematic (200 Hz) and kinetic (1000 Hz) data during soft, normal and stiff-knee landings (Study I) and for under, normal, and over-stride running (Study II). Performance trials were tested for normality, condition differences were documented and multiple regression models were computed to predict the first (F1) and second (F2) maximum vertical forces during landing and the maximum impact force (IF) during running. Results of the study identified condition differences with no deviations from normality, thereby achieving the goal of increasing performance heterogeneity to benefit the modeling procedures. Group regression model results for F1, F2 and IF each identified a single predictor variable that accounted for 74.7, 98.6 and 81.6% explained variance (EV), respectively. Single-subject predictors and EV values varied and demonstrated a number of different strategies. The group models were not representative of any of the individual subjects' performances and indicate that group models can describe a mythical "average" performer. These results suggest that researchers must be cautious when evaluating group performance patterns.

1. Review and theory

The concept of within-subject experiments is certainly not a new one. The intensive study of the individual dates back to the mid-1800s (Barlow and Herson, 1984). Even though the individual has been the emphasis for some researchers, the dominant contemporary methodology focuses on inferential (group) statistical analyses, developed in large part by Fisher, which allow for generalizability of results. A primary disadvantage of this approach is its potential to de-emphasize the importance of the individual. Predictions from the group model pertain to an "abstract" or "average" individual. To what extent then is this model representative of any one individual in the group and how important are observed deviations between individual and group results?

In order to infer from the sample to the population, the sample must be representative of the population which in turn requires a more homogeneous group which then limits generalizability of results. How restrictive this becomes depends upon the task and the individuals performing the task. In the extreme case, one could argue that no two individuals come to the experimental setting with **exactly** the same experiences, perceptions, and expectations and therefore no "homogeneous group" exists. It follows from this viewpoint that the individual must therefore be the focus of all experiments. This conclusion is certainly not always appropriate and more likely to be the case in areas such as high level performance, injury, therapy, and learning. In these instances, any deviation between the individual and the "group" might be unacceptable.

Variability is an inherent component of movement both within and between subjects. Intra-subject variability affects the reliability of individual scores and can have a significant effect on the statistical power of an experiment (Dufek et al., 1995). This variability can be controlled by imposing additional experimental constraints and/or by incorporating multiple measurements or trials. Inter-subject variability can have a similar effect (Bates et al., 1992) if it is simply the result of greater or lesser variations among individuals performing the same task in a similar manner. A more difficult situation arises, however, when the variations are the result of individuals using different solutions (strategies) to accomplish the same task.

A strategy is a selected neuro-musculo-skeletal solution for the performance of a task. Movement patterns for a given individual are constrained by peripheral sources of variation including morphology, the environment, and mechanics (Berstein, 1967; Higgins, 1977). A selected strategy is influenced by a person's previous experiences, their perceptions, and the resulting expectations. Although strategies are learned, they can be considered to be stable response patterns during the course of many experiments. Considerable experimental evidence in support of individual strategies can be found in the research literature (Bates et al., 1979b; Caster and Bates, 1995; Dufek et al., 1991; Jensen and Phillips, 1991; Lees and Bouracier, 1994; Loslever, 1993; Reinschmidt and Nigg, 1995; Schlaug et al., 1994; Worringham, 1993). Performance differences (inter-subject variability) resulting from different strategies threaten the external validity of a group design and often lead to false support for the null hypothesis (Bates, 1989).

Given these concerns, a possible approach for avoiding these potential problems is to combine group and single-subject designs to gain additional insight into the research problem of interest. The current study takes this approach. It is exploratory in nature and was not designed to find a definitive answer but to gain a better understanding of human performance.

2. Performance factors: Impact phenomena

Macaulay (1987) has stated that the human body is a complex machine and that its functional responses to impact are not well understood. The multiple functional degrees of freedom that exist for an individual to perform any movement task lend support for this statement. Attempts to gain understanding of mechanisms of impact force attenuation (functional responses to impact) have been reported for both running and landing performance - two common movements that exhibit a definite impact phase. Running has been the focus of biomechanical investigation for a number of researchers (e.g. Bates et al., 1979a; Bates et al., 1983; Cavanagh, 1990; Cheskin et al., 1987; Nigg, 1986) while landing has only more recently been the focus of investigation (e.g. DeVita and Skelly, 1992; Dufek and Bates, 1990,1992; McNitt-Gray, 1991,1993; Schot et al., 1994).

The impact force observed during the first 50 ms of ground contact for runners using a heelstrike pattern has been implicated as a major cause of running injuries (James et al., 1978; Perry, 1983; Nigg, 1985; Van Mechelen, 1992). Changes in the magnitude of the impact force have been associated with factors such as running shoe characteristics, running speed, surface, and running technique (Bates et al., 1983; Bowers and Martin, 1974; Clarke et al., 1983; Hamill et al., 1983; Nigg et al., 1987; Hennig et al., 1993). However, individual adaptations to factors influencing impact force are not well understood.

Several of the above mentioned running impact studies found no significant differences between conditions which appears contradictory to medical anecdotal evidence (James et al., 1978; Becker, 1989; McKenzie et al., 1985; James and Jones, 1990). It has been suggested that a lack of statistical significance can be attributed to reported variations in the motor program that is used to accommodate to environmental changes introduced during running (Clarke et al., 1983; Nigg et al., 1987; Nachbauer and Nigg, 1992). An alternative explanation is that differences could have been masked as a result of grouping subjects who used differential response strategies (Stergiou and Bates, 1994; Bates and Stergiou, submitted). Other factors which also could have influenced these results include nonrepresentative data on individual subjects due to an insufficient number of performance trials, improper statistical design and/or a general lack of statistical power (Bates, 1989; Bates et al., 1992; Dufek et al., 1995).

Investigations into landing have documented several factors that influence performance. Mass added to the ankles resulted in the identification of two extreme categories of responses termed strategies (Bates and Caster, 1989; Caster and Bates, 1995). Similarly, increased task demands in the form of height (gravity) and distance (angular momentum) coupled with varying degrees of knee joint flexion (lower extremity "stiffness") resulted in different subject-responses with respect to observation of impact force values (Dufek, 1988; Dufek and Bates, 1990; Dufek and James, 1994). McNitt-Gray (1991, 1993) documented skill-related kinematic and kinetic differences for individuals landing with equal vertical contact velocity values. Surfaces have also been documented to affect landing impact characteristics (Dufek et al., 1991; McNitt-Gray et al., 1994). These results strongly suggest that the previous landing experiences of the individual subjects influence the observed empirical outcomes and suggest a need to attend to individual subject differences in whatever form (morphological, cognitive, behavioral) when attempting to generalize results.

Human performance response patterns to different environmental factors (eg, footwear, running speed, landing height) can range along a continuum from completely ignoring the varying demands of the task (Newtonian or mechanical response) to total accommodation (neuromuscular response) with most patterns being somewhere between these two extremes (Bates et al., 1988; Caster and Bates, 1995; Simpson et al., 1988). A pure or partial Newtonian response will produce varying impact force values while a pure neuromuscular response will result in consistent impact force values across conditions. The chosen response by an individual will depend upon recognition of the existence of the perturbation and perception of its potential effects upon the system. Assessment of the potential system effects is based upon knowledge (or lack thereof) obtained through previous experiences. If the potential system effects are deemed imperceptible, no change in performance will be elicited (Newtonian response). Alternatively, if a modification is perceived to be necessary, the lower extremity kinematic patterns and the stiffness characteristics of the involved musculature will be modified. Due to the numerous functional degrees of freedom of the human machine, a great number of responses are possible which lie somewhere along a continuum between these extremes (Newtonian to neuromuscular).

Prior research into the impact phase of running and landing suggests that: (1) little is known about the mechanisms of impact force attenuation, and (2) individual subjects with unique movement histories j experiences tend to influence the empirical results obtained. In order to learn more about the mechanisms of lower extremity impact force attenuation, two similar but independent studies were undertaken. Study I incorporated the activity of landing while Study II invoked the activity of running. The purpose of both studies was to evaluate and compare individual lower extremity response patterns (strategies) to perturbations during impact activities. Both group and individual subject performance outcomes were evaluated to assess similarities between the two methodological approaches.

3. Study I

3.1 Methods

Data acquisition

Six male volunteer subjects granted written consent in accordance with the policies established by the Committee for the Protection of Human Subjects at the affiliated AAU institution. Reflective markers were placed at appropriate body landmarks. Following a self-directed warm-up, each subject performed three variations of step-off landings from a 0.6 m height onto a dual AMTI force platform system (one foot per platform). Kinematic information from the right side was simultaneously obtained using a high speed real time video data acquisition system (Motion Analysis, 200 Hz). The first experimental manipulation (NOR) consisted of 30 landing trials using a self-selected technique. For the second and third variations, consisting of 10 trials each, subjects were instructed to land as softly (SO) or stiffly (ST) as possible using the knee joint to manipulate performance outcome. Right side vertical ground reaction force (vGRF) values were obtained (1000Hz) and evaluated during the impact phase of landing (100 ms post-contact). Two vGRF variables were identified (first [F1] and second [F2] maximum values), normalized to body mass and used for subsequent analysis. Retro-reflective images of the previously applied markers, illuminated via a spotlight aligned with the optical axis of the video camera, were translated to space coordinates using a Motion Analysis VP320 video-processor interfaced to an IBM-compatible computer. Kinematic data were processed (digital filter, 10 Hz), synchronized and interpolated to the force platform data and 45 lower extremity kinematic independent variables (IVs) were computed using laboratory software. Angular conventions adopted were those of Winter (1990) with plantarflexion, knee and hip joint flexion represented by positive values. Kinematic time-histories were visually inspected to verify computational and synchronization procedures.

Data analysis

The effects of the experimental manipulations (knee joint flexion) on landing performance were first assessed using single-subject analyses of variance (ANOVAs). For subjects with observed significant ($\alpha = 0.05$) omnibus *F*-values, follow-up Model Statistic procedures (Bates et al., 1992) were incorporated to identify specific condition differences. Normality of individual subject-generated performances across conditions was evaluated with the Shapiro-Wilk (*W*) test (Shapiro and Wilk, 1965). The purpose of this evaluation was to justify collapsing the data across conditions for subsequent regression analyses.

Modeling procedures in biomechanics generally embrace one of two approaches: mechanical or mathematical/statistical. A statistical modeling procedure, using stepwise multiple regression, was incorporated to develop the models in this study. An overall $\alpha = 0.05$ level was established for model significance, while a more liberal $\alpha = 0.15$ level was adopted for initial variable inclusion into the model. Both F1 and F2 were defined as dependent variables (DVs) representing the impact phase of landing. Regression models were computed for the total data set only as previously indicated to maintain adequate trial to IV ratios.

The rather large kinematic variable set (*n* = 45) was systematically reduced to produce a non-redundant set of IVs representative of landing performance across all subjects. The procedure used to reduce the IV set included computation of within-subject IV vs DV correlation matrices. First, all IVs with correlation coefficients not significantly different from zero ($\alpha = 0.01$) were eliminated. Next, all IVs that shared at least 25% common variance ($r \geq 0.50$) with the DVs (F1 and F2) across a minimum of four of the six subjects were retained for the prediction models. This process resulted in seven and nine IVs to predict F1 and F2, respectively (Table 1) and conservative 7:1 and 6:1 ratios of empirical observation: IV. Stepwise multiple regression models were then incorporated to predict F1 and F2 for the group (*n* = 6) and all individual subjects.

3.2 Results

Results of the single-subject ANOVAs identified all subject-DV comparisons to be significant ($p = 0.0001$), therefore Model Statistic *post hoc* tests were conducted to identify specific condition differences ($\alpha = 0.05$). Results of these analyses identified significant differences for 92.7% of the condition comparisons. Only one subject-condition comparison was not statistically significant (S2: NOR vs ST). These results led to the question of whether the experimental conditions actually extended the range of landing performance (heterogeneity) or whether the performance changed and a new skill or task was invoked. In order to address this question, all single-subject F1 and F2 data sets were tested for normality using the Shapiro-Wilk (W) procedure. The average W values across all subjects were 0.941 and 0.934 for F1 and F2, respectively, suggesting a strong tendency for normality among the 50 data trials for each subject. Therefore, it was assumed that the experimental protocol succeeded in producing a set of performance trials that fell along a continuum that was expanded due to the imposed experimental perturbations and not the result of different trials/skills. Mean values (SDs) for all subject DVs and IVs collapsed across conditions are given in Table 1. A representative example of six of the 50 force-time histories for an exemplar subject is given in Fig. 1. These curves represent the continuum of responses by this subject (S1).

A comparison of group and single-subject impact force values by condition are shown in Fig. 2. These data suggest that the group and most all subject performances incorporated a Newtonian component, with increased impact force values in response to increased task demands. Exceptions to this generalization exist for S5 and S6 who each adopted a different landing style (flatfoot) for selected conditions (S5: NOR; S6: NOR and ST).

Table 1
Landing: Mean and standard deviation values by subject for kinetic and kinematic variables

Variable	S1	S2	S3	S4	S5	S6
F1	19.17	13.68	11.98	10.38	13.19	9.26
	(3.09)	(1.23)	(2.78)	(1.84)	(2.37)	(0.77)
F2	25.97	25.46	25.77	37.20	33.83	58.06
	(6.70)	(6.01)	(5.96)	(5.82)	(15.34)	(14.89)
Ankle						
θ Con [a]	33.49	23.43	29.24	24.78	20.16	−7.91
	(2.80)	(2.46)	(3.34)	(2.47)	(13.98)	(13.55)
Vv Con [a]	−4.57	−4.69	−4.35	−4.53	−4.49	−3.67
	(0.17)	(0.19)	(0.32)	(0.18)	(0.57)	(0.55)
Vh T1 [a]	−1.24	−1.18	−1.04	−0.96	−1.39	−0.74
	(0.32)	(0.38)	(0.31)	(0.31)	(0.32)	(0.24)
Av T2 [b]	139.1	133.7	143.7	176.3	171.5	235.34
	(30.5)	(38.9)	(28.8)	(16.0)	(55.0)	(42.12)
Knee						
θ Con [ab]	23.96	25.55	28.22	22.43	22.09	35.80
	(2.97)	(3.32)	(3.19)	(4.48)	(3.70)	(3.26)
Vv Con [a]	−4.91	−4.99	−4.65	−4.84	−4.86	−4.43
	(0.14)	(0.20)	(0.25)	(0.17)	(0.42)	(0.36)
ω Con [b]	486.1	322.8	451.6	410.6	473.8	516.2
	(86.9)	(87.4)	(107.8)	(64.7)	(90.8)	(133.9)
θ T1 [a]	30.01	29.39	33.44	26.43	28.07	36.40
	(3.64)	(3.24)	(3.71)	(4.52)	(5.01)	(3.01)
θ T2 [b]	51.96	46.98	53.86	42.25	44.92	44.29
	(6.06)	(4.17)	(5.16)	(4.87)	(11.71)	(4.26)
Av T2 [b]	157.24	164.76	158.04	201.83	174.78	225.21
	(23.73)	(46.79)	(24.26)	(13.94)	(44.93)	(36.37)
Hip						
Av T1 [a]	20.94	−5.47	7.79	−11.22	6.48	−21.10
	(23.71)	(18.27)	(17.97)	(13.81)	(8.29)	(9.16)
θ T2 [b]	36.12	38.59	36.62	28.83	30.84	30.08
	(4.85)	(2.99)	(4.67)	(4.70)	(6.78)	(4.07)
Vv T2 [b]	−3.90	−4.43	−3.97	−4.63	−4.33	−5.09
	(0.54)	(0.79)	(0.50)	(0.49)	(0.38)	(0.29)
Vh T2 [b]	−0.21	0.35	−0.09	0.32	0.20	0.88
	(0.31)	(0.31)	(0.19)	(0.17)	(0.27)	(0.26)
Av T2 [b]	84.27	87.49	74.93	90.35	90.95	82.74
	(18.27)	(24.40)	(23.17)	(26.11)	(22.98)	(25.80)

[a] IVs used in F1 model prediction.
[b] IVs used in F2 model prediction.
Units: F1 and F2 = N/kg; θ = deg, ω = deg/s, Vv and Vh = m/s; Av = m/s/s; See appendix for abbreviations.

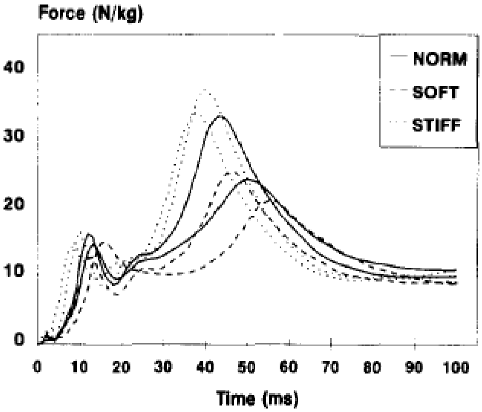

Fig. 1. Landing: Representative vGRF–time histories for an exemplar subject (S1) illustrating same-skill performance across conditions.

In these cases, no F1 value was observed and associated F2 values were therefore much greater. An observed F1 neuromuscular response for S2 (NOR vs ST) was also demonstrated, however, it should be noted that this was the only non-significant condition-comparison across all subjects. These results are consistent with the normality results across conditions and support the within-subject regression approach for all subject-DVs except possibly F1 for SS and S6.

Group multiple regression models using subject-condition mean values generated for all trials (*n* =50) elicited significant single variable prediction equations for both F1 and F2. The resulting F1 regression equation, [F1 = (Hip Av@T1 * 0.20) + 13.03], accounted for 74.7% explained variance (EV). The group prediction equation for F2 [F2 = (Ankle Av@T2) * 0.32 - 20.56] accounted for 98.6% EV.

Single-subject F1 prediction equations averaged 77.5% EV, with the exclusion of S6 (no significant F1 model generated). For F2, the average within-subject EV was 90.3%. The number of IVs entering the prediction equations that contributed at least 5% EV averaged 2.6 and 1.7 for significant F1 and F2 models, respectively. All IVs retained for analysis (see Table 1) entered at least one subject-DV model.

Results of the group- and single-subject regression models are comparatively summarized in Fig. 3. For F1, two subjects (S2 and S3) generally performed like the "group", with Hip Av@T1 accounting for 39.1 and 64.1% EV, respectively. Hip Av@Tl was a contributor for maximum forefoot vGRF (F1) for one additional subject (S1), however, it only explained 5.4% of the total impact phenomena. Although SS performed different from the group, his model must be viewed with caution because of his greater response range across conditions. Comparative group versus single-subject model composition for F2 presents a much stronger argument against the appropriateness of the group model for explanation of maximum rearfoot vGRF values (F2) at the level of the individual subjects.

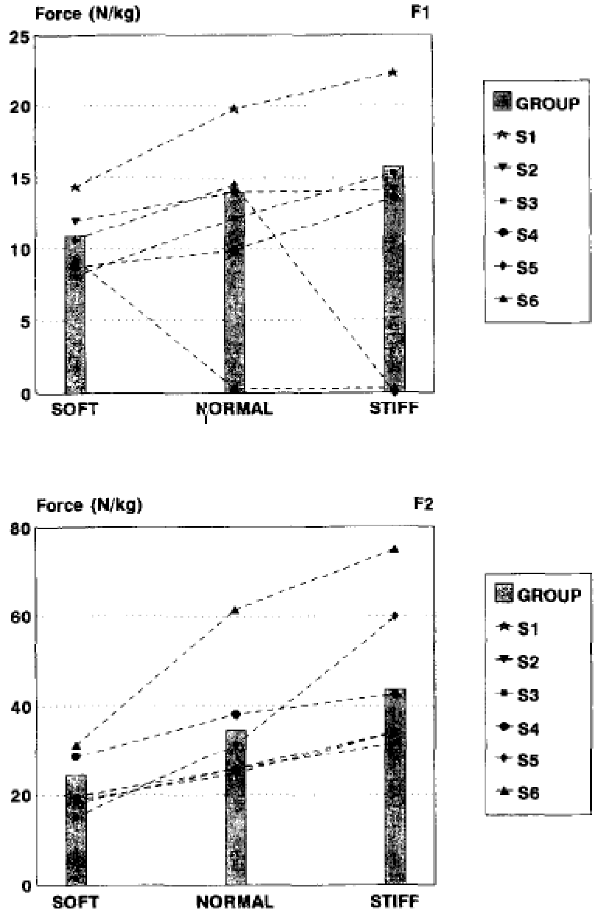

Fig. 2. Landing: F1 (top) and F2 (bottom) group and single-subject mean condition values. Group values are shown in histogram form with individual subject values indicated symbolically.

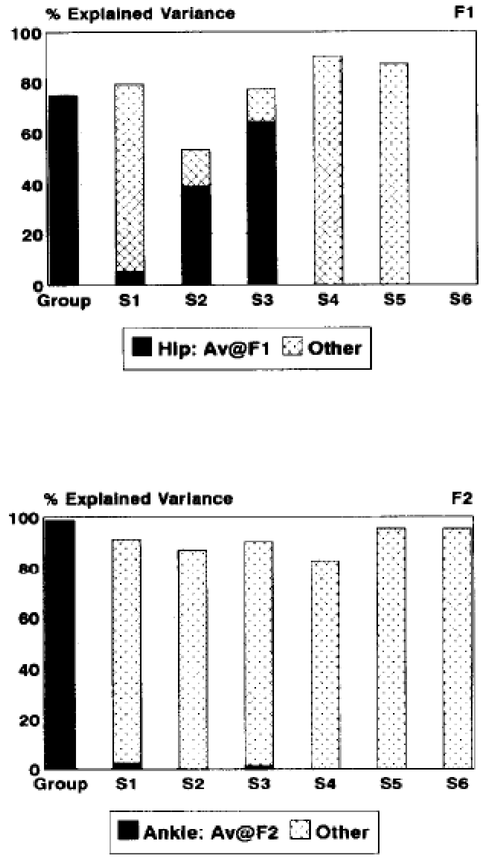

Fig. 3. Landing: F1 (top) and F2 (bottom) prediction models illustrating comparative strength and composition of group and single-subject prediction models.

Prediction models for only two subjects (S1 and S3) contained the group primary predictor variable (Ankle Av@T2) and this variable accounted for a mean EV for these two subjects of only 1.6%.

The single-subject prediction models are summarized by number of IVs, primary IV contributor to total EV, and performance strategy in Table 2. These data illustrate the differences in subject performances as well as the greater "complexity" of the models versus the single-variable models elicited for the group. The strongest prediction models for F1 were generated for subjects performing with a dominant "ankle" strategy (average 88.6% EV). For F2, the weakest model was observed for the "knee" strategy (S4: 82.8% EV) while EV across the other two strategies (hip and hip/knee) averaged 91.9%.

Table 2
Landing: F1 and F2 single-subject prediction model summary

	S1	S2	S3	S4	S5	S6
F1						
# IVs (> 5% EV)	3	3	2	2	3	*
Primary	K:Vv	H:Av	H:Av	A:Vv	A:Vv	*
Strat	"K"	"H/K"	"H/K"	"A"	"A"	*
Model EV	79.2	53.5	77.3	90.2	87.1	*
F2						
# IVs (> 5% EV)	2	3	1	2	1	1
Primary	K:Av	H:Vv	H:Av	K:θ	H:Av	H:Vv
Strat	"H/K"	"H"	"H"	"K"	"H"	"H/K"
Model EV	91.3	87.0	90.2	82.8	95.4	95.3

* = no significant model.
Primary = IV with greatest EV contribution;
Strat = performance strategy;
Model EV in percent;
See appendix for additional abbreviations.

4. Study II

4.1 Methods

The research protocol used for Study II attempted as in Study I, to create a more heterogeneous performance sample for each subject. This was accomplished by imposing moderate perturbations on normal running stride length by requiring specified trials to be slightly shortened (understride, US) or elongated (overstride, OS). This procedure has the potential to create three independent conditions, each representing a separate skill similar to the landing protocol. However, given a successful experimental manipulation (all trials representative of the same "skill" of running) the creation of a more heterogeneous sample will enhance modeling capabilities for the statistical techniques incorporated.

Data acquisition

Six different male volunteer subjects granted written consent in accordance with the policies established by the Committee for the Protection of

Human Subjects at the affiliated AAU institution. After each subject established a self-selected pace and while performing their warm-up, a right foot marker was placed one stride length before the force platform. The marker was moved 0.30 (± 0.03) m or approximately one foot length (anteriorposterior axis) closer and farther from the force platform for the US and OS variations, respectively. This distance was established via a pilot study which indicated that for these subjects to maintain a heelstrike running pattern, the US/OS variations could not deviate from the NS condition by more than one foot. For both the US and OS variations, subjects were instructed to target both the marker and the force platform. The testing session consisted of 30 trials of NS running and 20 trials for each of the OS and US variations, for a total of 70 trials per subject. For all three conditions, the subjects ran with a heel-toe footstrike pattern at their preferred running pace, while being monitored by a timing light system (± 5% target pace).

An AMTI force platform (1000Hz) was used to obtain ground reaction force data. The first maximum vertical ground reaction impact force (IF) was identified and quantified for analysis. In addition to the kinetic data, simultaneous kinematic data were obtained using two NAC high-speed video cameras (200 Hz) interfaced to a real-time Motion Analysis System. The cameras were positioned to obtain both a right sagittal and a rear view of the right lower extremity during the support phase. Kinematic data acquisition procedures were similar to those previously described for Study I. The obtained space coordinates were scaled and smoothed using a digital filter with a selective cut-off algorithm (Jackson, 1979). The cut-off values were between 14 and 20 Hz for the rearfoot coordinates and between 10 and 14 Hz for the sagittal view coordinates. Kinematic data were then computed from the smoothed position coordinates using laboratory software.

Data analysis

Data analysis procedures were similar to those used to evaluate the landing data with some minor variations as identified. IF condition mean values were evaluated ($p < 0.05$) for the group and individual-subjects using ANOVAs and an individual subject technique (Model Statistic; Bates et al., 1992), respectively. The combined IF data sets for each subject were next evaluated using a curve correlation technique (Shapiro and Wilk, 1965; SAS, 1993) to determine whether or not the three conditions could be combined, i.e., whether all trials represented the same "skill" of running. IF prediction models for the group using subject mean data and for each subject using individual trial data were generated for the total data set ($n = 70$) using multiple regression techniques. Twelve kinematic IVs (Table 3) were identified for use in the modeling procedure based upon the running literature and pilot work. The selection of IVs was further confirmed through correlations with the dependent variable (IF), resulting in 72.2% significant correlations (*r* values) for all subject-variables. The number of significant *r* values within-subject ranged from 50.0 to 91.7% with 37.5% of all values exceeding an absolute *r* value of 0.50. The IV set was limited to 12 in order to maintain a minimum 5:1 ratio between the number of subject-trials and predictor variables (Pedhazur, 1982; Stevens, 1986). The results of these regression analyses were evaluated to identify possible group- and single-subject performance strategies.

Table 3
Running: Mean and standard deviation values by subject for kinetic and kinematic variables.

Variable	S7	S8	S9	S10	S11	S12
IF	18.92	14.77	20.28	16.70	19.12	20.21
	(3.39)	(4.63)	(3.52)	(1.44)	(3.11)	(2.83)
T1	0.0386	0.0265	0.0381	0.0409	0.0381	0.0279
	(0.004)	(0.006)	(0.003)	(0.006)	(0.003)	(0.005)
Ankle						
Vh Con	1.65	1.61	1.54	1.93	1.72	1.47
	(0.32)	(0.57)	(0.21)	(0.19)	(0.26)	(0.43)
Vv Con	-1.16	-0.98	-1.06	-1.11	-1.05	-1.49
	(0.20)	(0.38)	(0.37)	(0.22)	(0.21)	0.29
Av Con	6.74	8.22	7.09	10.73	8.68	12.97
	(5.70)	(5.82)	(4.07)	(4.46)	(4.59)	7.89
Knee						
θ Con	171.0	159.3	166.6	164.5	169.2	163.7
	(7.83)	(6.91)	(2.13)	(6.57)	(2.66)	(7.54)
θ T1	154.0	151.1	155.8	152.2	158.9	157.4
	(4.16)	(7.61)	(4.30)	(4.01)	(3.60)	(4.29)
ω T1	-491.0	-357.3	-423.4	-530.6	-446.5	-301.6
	(103.5)	(79.29)	(83.85)	(156.7)	(74.74)	(166.0)
Vv Con	-0.74	-0.64	-0.76	-0.89	-0.75	-1.02
	(0.24)	(0.16)	(0.25)	(0.19)	(0.17)	(0.25)
Vh Con	3.53	3.66	3.19	3.37	3.26	3.34
	(0.23)	(0.25)	(0.23)	(0.17)	(0.19)	(0.26)
Av Con	-7.29	-10.29	-11.55	-14.38	-4.91	-7.59
	(4.93)	(6.44)	(4.42)	(5.48)	(5.30)	(8.20)
L θ Con	100.60	96.98	97.68	100.0	99.02	97.92
	(2.28)	(3.91)	(2.38)	(2.16)	(1.56)	(3.31)
P ω T1	-177.5	-366.6	18.94	-70.59	-277.6	-379.0
	(98.6)	(228.8)	(169.6)	(203.5)	(112.8)	(110.2)

Units: IF = N/kg; T1 = s; θ = deg, ω = deg/s, Vv and Vh = m/s; Av = m/s/s; See appendix for abbreviations.

Table 4
Running: Single-subject mean and standard deviation IF values by condition

	US	NS	OS
S7	17.9 [ab]	16.4 [c]	23.3
	(1.6)	(1.5)	(1.9)
S8	14.8 [ab]	10.9 [c]	21.8
	(1.8)	(1.0)	(2.5)
S9	16.9 [ab]	19.5 [c]	25.2
	(1.3)	(1.8)	(1.5)
S10	17.8 [ab]	15.8 [c]	17.1
	(1.2)	(1.0)	(1.3)
S11	15.5 [ab]	19.5 [c]	22.5
	(1.4)	(1.7)	(1.7)
S12	18.8 [ab]	20.9	21.1
	(1.8)	(2.2)	(3.4)
Group mean	16.8 [b]	17.2 [c]	21.8
	(1.4)	(3.6)	(2.7)

[a] US ≠ NS, [b] US ≠ OS, [c] NS ≠ OS at $p < 0.05$;
Units = N/kg.

4.2 Results

The group and individual-subject mean IF values by condition are given in Table 4. The group results indicated no significant difference between the US and NS conditions while the OS condition was significantly greater than both US and NS. Single-subject comparisons resulted in significant differences for all but one (94.4%) paired comparison.

Group and individual condition responses are shown in Fig. 4. The order (US, NS, OS) was based upon an expected increase in IF values assumed to be associated with increased demands of the activity relative to stride increases. This increase was not confirmed by the group mean values, however, since US and NS were not significantly different. Independent of the ordering of the data, three general subject response patterns/strategies were observed. S9 and S11 exhibited increasing IF values suggesting the anticipated predominantly Newtonian response pattern. S12 exhibited this same response between US and NS but then accommodated via a neuromuscular response to the demands of the OS condition. The remaining three subjects (S7, S8, S10) appeared to associate greater demands with both non-normal conditions (US and OS). None of the individual subjects performed using the "group" or "average" individual strategy.

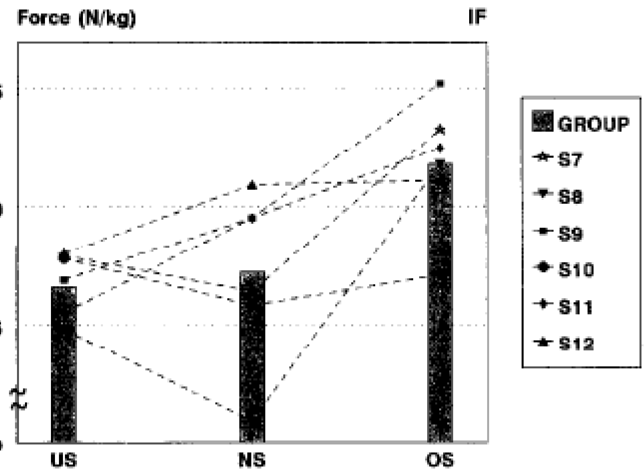

Fig. 4. Running: Group and single-subject mean condition IF values.

Similar to the landing results, these condition-comparison results initially suggest that the conditions represent different skills and should not be grouped for further analysis. To verify or reject this conclusion, the grouped data sets were evaluated using a curve correlation technique that compared the grouped distribution with a normal distribution (Shapiro-Wilk (*W*) procedure). The average *W* value across all subjects was 0.938 with the lowest *W* = 0.910 (S7). These results suggested a high degree of similarity between the individual-subject data sets and presence of a normal distribution. Therefore, all sets of subject data were grouped and retained for the regression analyses.

The group regression equation [(Kneeθ@T1 * 0.49) - 56.94] identified a single predictor variable for IF, accounting for 65.1% EV (α = 0.052). Results from the single-subject regression analyses are summarized in Table 5. The group EV value was slightly greater than the mean subject EV (64.9%) but less than three of the individual subject models (S7, S8, S9). The subject models included an average of 3.8 variables with individual predictor variable EV values ranging from 9.4 (S1O) to 86.3% (S8). Each subject-model was unique with nine of the 12 total predictor variables (Table 3) entering different individual models. The primary single-subject predictor variables were Ankle-Vv@contact (S8, S9, S10, S11, S12) and Knee-Vv@contact (S7, S8, S12). The mean EV for these variables across single-subject models was 45.1% however, there was considerable similarity between the models for the two subsets of subjects (S7, S8, S1O and S9, S11) that exhibited the same performance strategies for the dependent variable (IF). Of the 23 variables entering the individual models, 13 exhibited simple correlation coefficients with IF greater than r = ± 0.50. The two primary single-subject predictor variables (Ankle-Vv@contact and Knee-Vv@contact) produced a mean correlation of r = -0.81 (excluding S10). Finally, it should be noted that the single group model predictor variable (Kneeθ@T1) did not enter any of the single-subject models.

Table 5
Running: Single-subject IF regression model summary

Variable	S7	S8	S9	S10	S11	S12
T1	*			*		$
Ankle						
Vh Con			#		#	$
Vv Con		*	#	*	#	$
Av Con						
Knee						
θ Con						
θ T1						
ω T1	*					
Vv Con	*	*				$
Vh Con	*	*				
Av Con	*	*				
L θ Con		*	#			$
P ω T1	*	*				
Model EV	90.1	92.9	91.0	30.7	83.0	78.4

* = predominantly Newtonian between NS and both US and OS.
# = predominantly Newtonian response.
$ = predominantly Newtonian to neuromuscular accommodating response;
Model EV values in percent;
See appendix for abbreviations.

5. Discussion

The primary aim of the study was to evaluate and compare individual lower extremity response patterns (strategies) to perturbation during impact activities. Both group and individual subject performance outcomes were evaluated to assess similarities between the methodological outcomes. Similar experimental methodologies were incorporated for two studies using different subjects to perform normal and perturbed landing or running activities. Independent of the movement examined, results led to a similar conclusion - group models formed to predict impact forces created an "average" performance profile while individual subject impact force prediction models created profiles representative of the individual "strategies" invoked by each performer. Evaluation of the individual profiles across subject-activities illustrated both similarities and differences in the models among subjects.

Examination of the relationship between the landing impact force values elicited by the group and individual subjects (Fig. 3) demonstrated predominantly Newtonian responses to the imposed perturbations - increased impact force values corresponding to increased task demands. This result taken in isolation could lead to an errant conclusion that all subjects responded similarly and could therefore, be "grouped". A flaw in this thinking is demonstrated by examining the data in Table 2 for the individual-subject predictor models. These data illustrate the use of various strategies both among and within-subjects (between F1 and F2). One might hypothesize that the subjects in this experiment all responded externally in a predominantly Newtonian fashion, but found unique internal solutions to the imposed task constraints. The "average performance" group model solution does little to explain the performance mechanisms of lower extremity function during impact activities for the individual subjects.

Results for predicting single-subject IF values during running were also unlike those of the group. Specifically, the results support the premise that subjects perform differentially. These different response patterns are presumably linked to past experiences, recognition of the perturbation and a perceived need to respond. Identification of three different (external) responses does not support the hypothesis proposed by other researchers that adaptation is a consistent and universal mechanism used by individuals (Nachbauer and Nigg, 1992; Nigg et al., 1987; Nigg and Segesser, 1992). The differential response patterns observed in both Study I and Study II seem perfectly reasonable since it is unlikely that the subjects came to the experimental settings with the same experiences, therefore, it is unlikely that they would all have the same perceptions of the environment (lower extremity stiffness, different stride lengths) and respond with the same neural adjustments. It is more likely that different response patterns will be observed along the proposed continuum from purely Newtonian to totally neuromuscular. The results of this study support such a hypothesis. The observed unique response strategies may necessitate modification in the way we approach the study of some human performance problems.

Different subject response strategies can affect the statistical analysis results when a problem is approached only from the traditional group-design approach. A "dramatic" example can be observed in Fig. 4. Based on the group data, one might conclude that there were no differences between the US and NS conditions in Study II. However, Fig. 4 clearly illustrates that two subjects (S9, S11) exhibited a Newtonian component (increased IF) across the three conditions, while three subjects (S7, S8, S10) responded with a Newtonian component (increased IF) for both non-normal conditions (US and OS) relative to NS. By averaging all six subjects' data (group design) one obtains a neuromuscular response (US to NS) followed by a predominantly Newtonian response. This "average" does not accurately represent the effects of stride length modification on the observed IF values for any of the subjects.

The statistical modeling procedure invoked (multiple regression) as well as the associated procedures for identifying IVs to enter the model is not without limitation. Hamilton (1992, p. 73) identified two possible mistakes that a researcher can make: 1) including irrelevant IVs and 2) excluding relevant IVs. Care was taken in this study, using procedures to identify IV multicollinearity *a priori* (landing) as well as pertinent literature (running) to avoid the first "mistake". With respect to the second possible error, as is the case in any experiment, any possible "answer" obtained is limited by the form(s) of measurement employed. In a simple sense, muscular activation patterns, for example, could not be determined as primary predictors for landing or running impact forces in this study since they were not measured. Predictor variables were limited to kinematic measures (the effects of muscle activation patterns) as a first step in the modeling process.

With respect to the analysis approach embraced (multiple regression), it should be remembered that " ...the purpose of any study is to understand the data" (Stevens, 1986, p. 94). Therefore, several creative approaches were incorporated to learn about mechanisms of impact force attenuation in varying performance environments. It then follows that while various models are presented to predict impact force values for landing and running, these specific models might not be correct (due to limitations previously identified), but they still provide insight into lower extremity response mechanisms. These results suggest that considerable caution should be exercised when making interpretations based upon group model results. Group models should only be formulated when all subjects in the group produce the same external response using the same internal solutions to the imposed task constraints. This situation is highly unlikely, since subjects rarely enter an experimental situation with the same prior movement experiences. In addition, different individuals have unique anatomical constraints coupled with multiple functional degrees of freedom associated with the human link system which can be combined to produce multiple movement strategies that will influence performance outcomes.

6. Conclusion

The results of two independent experiments strongly suggest that prior subject experience coupled with adaptation to the movement environment (perceptions, expectations) can affect mechanisms of lower extremity function during impact activities. The individual-subject prediction models varied and performances demonstrated a number of different strategies. The group models were not representative of any of the individual subjects' performances and indicate that group models can describe a mythical "average" performer who in fact is not representative of any of the actual performers. Given unique subject movement-histories, it is possible to understand why subjects in any given experiment (e.g. Study I, Study II) do not perform similarly. The fact that group results do not accurately reflect individual performances naturally follows since, for example, a predominantly Newtonian response pattern by one individual could numerically counter a neuromuscular response pattern by another individual. It is imperative that researchers interested in the individual, whether from a performance enhancement, injury prevention or rehabilitation perspective, are sensitive to this shortcoming of group analyses and carefully evaluate their experimental design relative to their research question(s) before automatically incorporating traditional group evaluation procedures.

Appendix A

List of variable abbreviations

Abbreviation	*Definition*
F1	First maximum vertical ground reaction force: landing
F2	Second maximum vertical ground reaction force: landing
IF	First maximum vertical impact force: running
Con	Landing contact
Tl	Time of first maximum vertical ground reaction force
T2	Time of second maximum vertical ground reaction force
A	Ankle joint
K	Knee joint
H	Hip joint
L	Leg angle
P	Pronation angle
Vv	Vertical velocity
Vh	Horizontal velocity
Av	Vertical acceleration

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