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Relationship between physiological energy expenditure and biomechanical patterns associated with erect standing

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Abstract. The deviation of the static weight-bearing patterns under the feet of a lower extremity handicapped person may be measured quantitatively in terms of the Static Weight-Bearing Index. This paper describes the correlation between this index and the physiological energy expenditure associated with the erect standing posture. The Static Weight-Bearing Index can be conveniently used for evaluation of the functional status of the human lower extremity system in stance in case of lower extremity disabled persons who maintain basic weight-bearing mode involving both the limbs in double support condition.

Keyword. Static weight-bearing; performance evaluation; disability; energy expenditure; biomechanical patterns.

Introduction

Many studies on weight-bearing patterns of human feet have been aimed at assessing the success of treatment and effectiveness of rehabilitation in lower extremity disabled people as well as for exploring the fundamental biomechanical characteristics of the human lower extremity system. The studies on human locomotion have been concerned with the dynamic weight-bearing under moving feet (Fenn, 1930; Elftman, 1934; Schwartz and Heath, 1947,1949; Saunders *et al.,* 1953; Stokes *et al.,* 1974; Arcan and Brull, 1976; Miyazaki and Iwakura, 1976).The static weight-bearing patterns have been investigated upon using different techniques to correlate the variations in such patterns with the stance disability of these patients (Shambes and Waterland, 1970; Chodera and Sharma, 1977; Chodera and Cterceteko, 1979; Staros, 1965; Ghosh *et al.,* 1979; Tibarewala and Ganguli, 1982). Using a system of strain gauge load cells, a biomechanical evaluation of human lower extremity disability leading to defining of a Static Weight-Bearing Index as a quantitative measure of this disability during erect standing (to be published else where) was carried out. To evaluate the usefulness of this parameter it was necessary to correlate it with other established measures of human performance.

Abbreviations used: NG, normal group; LEH, lower extremity handicapped; PPC, post-polio cases; BKP, below-knee amputes using patellar-tendon-bearing prostheses; ACU, axillary crutch users; SWB, static weight-bearing; E, standing energy; BW, percentage body weight.

Measure of physiological energy expenditure by indirect calorimetery (Consolazio *et al.,* 1963; Durnin and Passmore, 1967) is considered as good as directed measurements. As performance is related to energy expenditure, an attempt was made to establish the relationship between the standing energy expenditure and Static Weight Bearing Index before recommending the latter for routine clinical applications.

Materials and methods

The test samples comprised of a normal group (NG) composed of 6 healthy, able-bodied, adult males with sedantry habits and a group of 23 lower extremity handicapped (LEH) consisting of 8 post-polio cases (PPC) affected on one side only, 6 unilateral below-knee amputees (traumatic) using patellar-tendon-bearing prostheses (BKP), and 9 auxiliary crutch users (ACU). The personal data of these subject groups have been presented in table 1.

Table 1. Personal data of subjects (mean±S.D.).

Group (number)	Age (yrs)	Height (m)	Body-weight (kg)	Weight of appliance (kg)
NG (6)	26.5±3.02	1.66±0.07	47.07±7.73	–
PPC (8)	21.1±3.4	1.55±0.05	39.73±5.96	–
BKP (6)	28.5±6.7	1.67±0.06	49.18±3.95	2.48±0.26
ACU (9)	25.11±3.9	1.62±0.07	48.01±7.09	2.53±0.26

Static weight-bearing (SWB) patterns under the feet of each subject were determined according to Tibarewala and Ganguli, (1982) and the SWB index was computed for each pattern according to Tibarewala and Ganguli (to be published else where). While a set of two indices (one for each foot) was determined for the subjects belonging to NG, BKP and PPC, only one SWB index (for healthy foot) along with the percentage of body weight transmitted through each crutch was determined for the ACU group. It may be noted that the method of measuring SWB patterns divides a foot into six parafrontal zones and measures the corresponding patterns as a set of six ordered numbers, each number representing the percentage body weight being transmitted through a particular zone. Further, SWB index for a particular pattern is the root-mean-square deviation of the set of numbers representing the mean normal pattern (Tibarewala and Ganguli, 1982).

The standing energy expenditure (E) was determined by indirect calorimetery (Consolazio *et al.,* 1963) and multiple regression analysis were conducted with E as the dependent variable. Since the list of independent variables for the NG, PPC, and BKP was different from that of ACU, two separate regression analyses were attempted; one for the ACU alone, and another for the combined group consisting of NG, BKP and PPC.

Results and discussion

In case of auxiliary crutch users, the scatter diagram representing the variation of standing energy expenditure E with the SWB index (figure 1A) indicated the presence of a linear trend. In terms of the correlation coefficient, a negatively linear regression with r =—0.5 might have been obtained, without considering any other factor. Inclusion of the percentage body weight (BW) transmitted through each crutch as additional independent variables led to a multiple regression equation (equation 1) with a value 0.68 for the multiple correlation coefficient. The estimated value of E from this equation have been plotted against the observed values in figure 1B.

$$E = 171.72 - 4.72\ \text{SWBI} - 8.85\ (\%\ \text{BW under the right crutch}) + 7.30\ (\%\ \text{BW under the left crutch}) \quad (1)$$

(R=0.68)

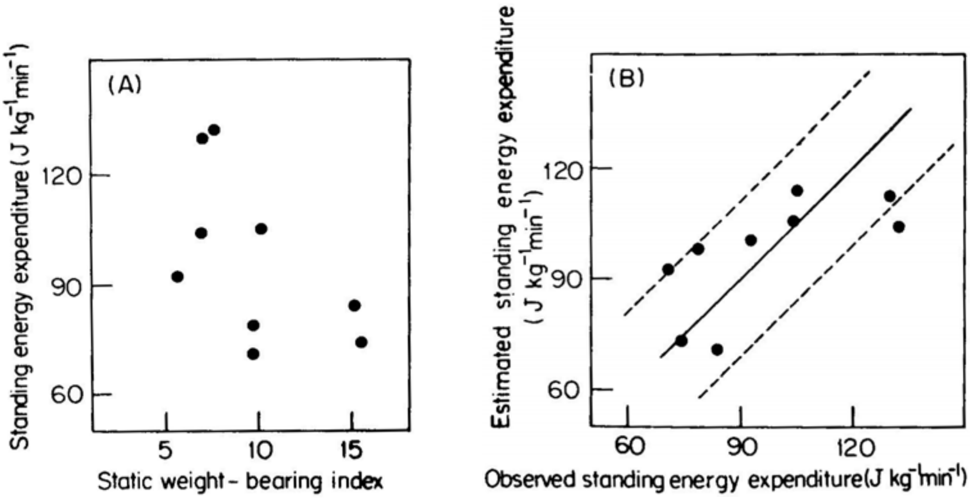

Figure 1. A. Standing energy expenditure *versus* static weight-bearing index (for auxiliary crutch users). **B.** Standing energy expenditure estimated from equation 1 *versus* observed standing energy expenditure (for auxiliary crutch users).

For the rest of the test subjects including NG, PPC and BKP, the standing energy expenditure has been plotted against the SWB indices in figure 2A. Since the values of the two SWB indices for the normals were nearly equal, an arbitrary choice was made to consider the left side of the normals with the healthy side of the LEH, and to specify the corresponding SWB index as SWBI (HS/L). Similarly, the right side of the normals was considered with the affected side of the LEH and the corresponding SWB index has been specified as SWBI (AS/R). Existence of linear correlation between the standing energy expenditure and the two SWB indices was apparent from this scatter diagram. This observation was further supported by computations whereby correlation coefficients between SWBI (HS/L) and E, and

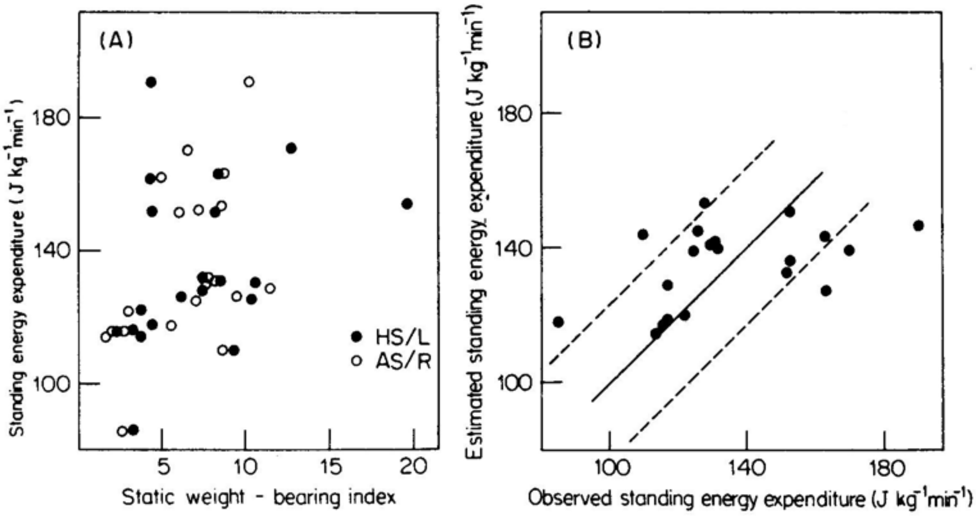

Figure 2. A. Standing energy expenditure *versus* static weight-bearing indices (for normals, below-knee amputees and post-polio cases). **B.** Standing energy expenditure estimated from equation *2 versus* observed standing energy expenditure (for normals, below-knee amputees and post-polio rehabilitees).

between E and SWBI (AS/R) were found to be 0.30 and 0.45 respectively. Multiple regression of E on the two SWB indices simultaneously improved the correlation coefficient upto 0.483. The partial correlation coefficients were found to be 0.114 between E and SWBI (HS/L), and 0.365 between E and SWBI (AS/R). This indicated the larger influence of SWBI (AS) compared to that of SWBI (HS) on the standing energy expenditure. The resulting multiple regression equation has been represented as equation 2.

$$E=106.372 + 0.653\ \text{SWBI (HS/L)} + 3.677\ \text{SWBI (AS/R)} \qquad (2)$$

The values of E estimated from this equation have been plotted against the observed values in figure 2B. As before, the central line and the dotted lines represent the ‘zero error’ estimates and the ‘standard error’ zone respectively.

The regression equation 1 has a negative coefficient of the SWBI which means that the standing energy expenditure of axillary crutch users decreased with an increase of the SWB index. This derivation is paradoxial in the sense that it demands a high energy expenditure with near-normal SWB patterns. This paradox, however, can be explained easily by considering the three point weight-bearing of the ACU which is very much different from the normal weight-bearing. The normal SWB pattern which is optimum for the two point stance, may not be so in the other case as a result of which any attempt of an ACU to adopt the optimum SWB characteristics with a three-point weight-bearing might have caused an increase of the deviation from the normal SWB pattern but a decrease in the standing energy expenditure rate. In case of the normals and the lower extremity handicapped other than ACU, however, the coefficients of both the SWB indices (in regression eg. 2) are positive indicating thereby that the standing energy expenditure increased with any increase in the deviation of SWB pattern from the mean normal pattern.

The regression analyses were repeated with different groups as separate strata whereby correlation coefficients between 0.3 and 0.8 were observed for each stratum, thus, eliminating the possibility of the observed correlation for the combined sample being spurious. Under such a situation, where the relationships having some amount of curvilinearity are approximated by linear regressions, it is safe to use the combined regressions rather than those obtained separately for each stratum (Cochran, 1977).

The regression equations obtained as a result of this investigation represent the relationships between the physiological energy expenditure incurred by the human body during erect standing—the most common static activity involving human lower extremity system, and the biomechanical measures of stance disability. Since the former have been recognised as reliable performance measures for long, the latter i.e. the biomechanical characteristics measured in terms of the SWB indices (and the portion of body weight transmitted through the crutches, in case of ACU) can now be used for performance evaluation of human lower extremity system in stance. On a comparative scale, an improved functional status in stance should be accompanied by lower values of the SWB indices. Because of entirely different three-point weight-bearing mode of standing, the functional status of auxiliary crutch users during the erect standing should not, however, be assessed on the basis of SWB index.

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Appendix

A brief description of the system used for determining the SWB patterns and the measuring procedure involved is represented here to provide an insight to the readers without elaborate reference:

Description of the system

The instrumentation of the system comprised three units, namely, the transducers, the interface and, the indicator as shown in figure 3A.

Six strain gauge load cells were used as the transducers. Each load cell was composed of four pressure dependent resistances connected in a Wheatstone bridge fashion. When supplied with a constant voltage across two of its terminals, an imbalance voltage proportional to the load applied to the elements of this circuit is provided at the other two terminals. These load cells were fixed on a wooden platform and each had a thin aluminium strip covered with rubber padding at the

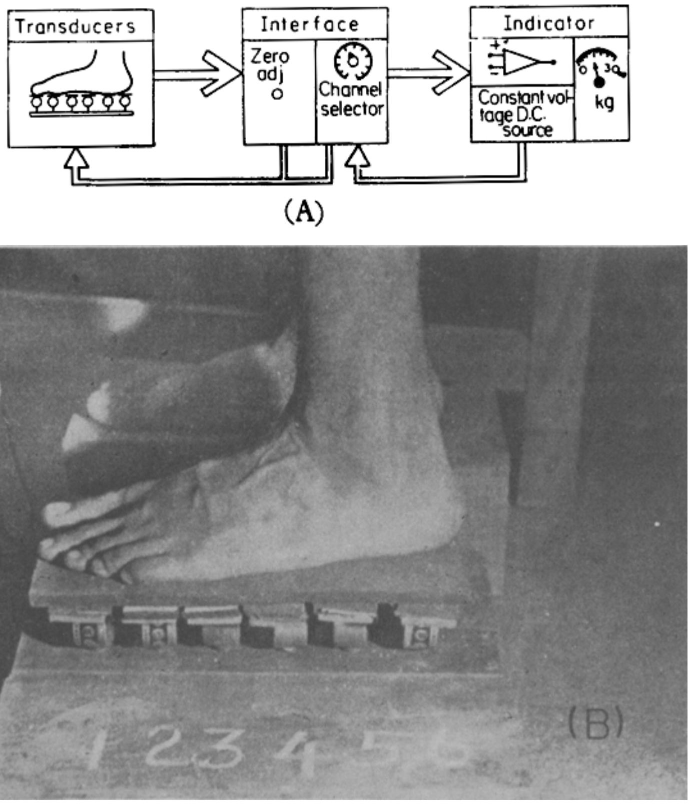

Figure 3. A. Flow diagram of the system for static weight-bearing studies. **B.** Placing the foot on load cell system.

top. The rectangular area thus formed by six parallel strips, constituted the support for the foot being investigated, while the other foot was supported by a dummy platform of matching area and height.

The interface served a dual purpose. Firstly, it contained a multi-pole selector switch, facilitating the activation of any one of the load cells at the investigators choice, thus making it possible to work with a single indicator. Secondly, it incorporated as its integrated portion, the arrangement for initial balancing (i.e. obtaining ‘zero’ output at ‘zero’ load on the load cells) of the Wheatstone bridge circuit. The indicator also had a dual role of a constant voltage source for the Wheatstone bridge supply and an amplifier-cum-display unit to indicate the imbalance voltage. The dial of the indicator was graduated directly in terms of kg.

Measuring procedure

Each load cell, with its corresponding part of the interface, was termed as one channel. Thus there were six numbered channels. The dummy platform and the load cell system were placed side by side so that the subject could stand with one foot on each, with toes placed towards channel 1 and heel towards channel 6 as shown in figure 3B. The selector switch was turned from 1 to 6 and the corresponding load displayed on the indicator dial was noted. The process was repeated thrice and the average load on each channel determined. Following this, the position of the dummy platform and the load cell system was interchanged and the whole procedure repeated to obtain the average distribution under the other foot. Finally, these weight distribution figures were normalized by the subject's body weight so that the SWB pattern under a foot may be expressed as an ordered set of six numbers, each number representing the percentage body weight being transmitted to ground through the relevant portion of the foot.

Static weight-bearing index

Any static weight-bearing pattern (or SWB pattern), being a set of six ordered numbers, may be represented by an unique point in a six dimensional hyper space with rectilinear orthogonal axes so that the distances from origin along the axes represent the corresponding ‘number’. This was the starting point of the approach. The points representing SWB patterns belonging to different types of feet formed separate clusters in different parts of the hyper space (to be published else where). Following this observation, it was felt that the difference between any two SWB patterns may be measured in terms of the distance between corresponding points in this space. In other words, the functional abnormality in erect standing may be measured by the departure of the corresponding SWB patterns from the mean normal pattern. Since the distance between two points in any space is a constant multiple of the root-mean-square (i.e. RMS), difference between the orthogonal rectilinear coordinates defining the points, a static weight-bearing index has been defined to measure the departure of any SWB pattern from the mean NG pattern as the RMS difference between the ‘numbers’ representing the two involved patterns.

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