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Use of the normalcy index for the evaluation of gait pathology

M. Romei [a,*], M. Galli [a], F. Motta [b], M. Schwartz [c,d], M. Crivellini [a]

[a] *Dipartimento di Bioingegneria, Politecnico di Milano, via Golgi 39, 20133 Milan, Italy*
[b] *Ospedale dei Bambini 'V. Buzzi', Milan, Italy*
[c] *Gillette Children's Specialty Healthcare, St. Paul, MN, USA*
[d] *Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, MN, USA*

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Abstract

The normalcy index (NI) has been proposed as a method for quantifying the amount of deviation in a subject's gait, compared to the gait of the average unimpaired person. The NI was computed for a sample of 144 children affected by cerebral palsy, five idiopathic toe-walkers and 12 able-bodied subjects. It was sensitive enough to distinguish unimpaired subjects from idiopathic toe-walkers and to distinguish between the plegic and uninvolved limbs of hemiplegic patients. The NI was robust enough to categorize pathology, ranging from mild disorders to quadriplegia. The NI was found to be clinically applicable, reliable and easy to use, making it a valuable element in the quantitative evaluation of gait pathology.

Keywords: 3D-gait analysis; Cerebral palsy; Normalcy index

1. Introduction

Gait analysis (GA) is widely recognized as a central element in the quantitative evaluation of gait, and in the planning of treatments for subjects with movement disorders such as those caused by cerebral palsy (CP) [2–4]. A typical GA study, however, yields a vast amount of data. This often makes GA an instrument that is complicated to use and difficult to interpret. There is a growing clinical awareness of the need for concise indices that allow an objective, quantitative evaluation of gait pathology. The literature contains several reports of index calculation procedures that make it possible to focus on a specific joint, a specific muscle, or on the function of a muscle group. One example is the method of Davis and DeLuca [5] for calculating an index of ankle joint stiffness. Frigo et al. [6] extended the use of this index to the hip and knee joints, identifying characteristics typical of hemiplegic and of diplegic subjects. In another example, Eames et al. [7] investigated the use of GA data in the study of specific muscles. Their study showed that kinematic data from the knee and ankle joints could be used to define the length of the gastrocnemius. The gastrocnemius length was estimated for a group of healthy subjects and a group of spastic (hemiplegic and diplegic) subjects. Their results revealed that the length of the gastrocnemius differed according to the type of spasticity.

GA has also been used to evaluate the function of groups of muscles. Schwartz et al. [8] set out to establish a concise index (hip flexor index, HFI) that could quantify hip flexor function during gait. The index was applied to a group of spastic subjects and the results demonstrated a close correlation between the results of HFI-based evaluation and of the clinical evaluations routinely performed by clinical experts. The index was then used in a retrospective outcome study to examine the effect of intra-muscular psoas lengthening [9].

These studies used data obtained from GA to focus attention on a specific pathological feature, such as the behaviour of a single joint. Often, in clinical settings, there is a need to find more general parameters that relate to a subject's overall gait pathology. Schutte et al. [1] proposed a normalcy index (NI), that characterises a patient's gait in a global sense. It uses multivariate statistical methods to quantify the extent by which a patient's gait deviates from that of an unimpaired control group. The NI is computed using standard multivariate statistical techniques (principal component analysis) applied to kinematic variables acquired using GA. Kinetic variables are excluded, as their use would render the calculation procedure inapplicable to subjects who rely on walking aids.

* Corresponding author. Tel.: +39-2-23993359.
E-mail address: romei@biomed.polimi.it (M. Romei).

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The procedure described by Schutte et al. [1] makes it possible to assign a single numerical value (NI) to the gait of a subject undergoing GA. Analysis of the NI can then yield useful information about the level of the subject's gait pathology. It is important to recognize that the NI is not diagnostic, nor does it identify the underlying source of the gait pathology. Rather, the NI allows a clinician to make a quantitative assessment of the amount of pathology present in a subject's gait. The NI can be used in several ways: to evaluate the range of pathology present in specific diagnoses, to compare a subject's gait to that of others with the same diagnosis, to track a subject's gait pathology over time, or to examine the effectiveness of an intervention.

Despite the fact that the NI is not diagnostic, it does quantify the differences in pathology present in populations with various degrees of impairment. In the study of Schutte et al. [1] the NI was applied to a series of 24 healthy subjects and 70 subjects affected by CP. It was found that the average NI for CP sub-types increased with the severity of the diagnosis. That is, the group mean NI of subjects with a less severe diagnosis (e.g. Hemiplegia) was lower than the group mean NI of subjects with a more severe diagnosis (e.g. Diplegia). The pattern followed by the group means was consistent, despite the fact that the ranges of NI for the groups overlapped.

The aim of the current study was to implement the calculation procedure for the NI to:

1) Verify the reliability of the method in unimpaired subjects.
2) Examine whether or not the index is independent of the instruments used in different laboratories.
3) Calculate the NI in a large series of children affected by CP to ascertain the usefulness of the NI in the characterisation of these subjects' gait.
4) Calculate the NI in pathological conditions not previously analysed.

2. Methods

The study was approved by the ethics committee of the 'V. Buzzi' Children's Hospital in Milan, and consent to participate in the study was obtained from the parents of all minors involved. Twenty-five subjects with no known gait pathology (mean age 14 years, range 7–28 years) underwent GA and formed the group needed to define the parameters of normal gait (Reference Group).

The GA tests were carried out at the 'L. Divieti' Posture and Movement Analysis Laboratory, Department of Bioengineering, Milan Polytechnic. Data was acquired using a 6-camera optoelectronic system with passive markers (ELITE, Bts, Milan, Italy [10]) working at a sampling rate of 50 Hz, and a single force platform (AMTI, MA, USA). Markers were positioned as described by Davis et al. [11], and subjects were asked to walk barefoot, at a self-selected speed, along a 10-m walkway containing a force platform at the mid-point. Ten trials were collected for each subject (five right foot and five left foot force plate strikes).

The required 16 kinematic gait parameters were extracted from the subjects' GA data. These were then processed, according to the published method, to obtain the NI. The mean values and standard deviations of the parameters obtained for the Reference Group were compared to those obtained by Schutte et al. [1]. The data obtained from the Reference Group were evaluated on a trial-by-trial basis to verify their reliability. They were also compared with the data of normal age-matched subjects reported in the Refs. [12,13]. Two trials per subject were selected, one for the right leg and one for the left leg, for a total of 50 trials. The data needed for the definition of the NI were extracted from these trials. An NI value was calculated for each member of the Reference Group. To verify proper implementation of the NI procedure, the distribution of the Reference Group NI was compared to a χ^2 distribution with 15 degrees of freedom (the theoretical distribution) [14,15].

A second unimpaired group (Able-Bodied Group) was selected from the existing database at 'L. Divieti' Posture and Movement Analysis Laboratory, Department of Bioengineering, Milan Polytechnic. The reason for selecting this second unimpaired group was as follows:

1) The NI is designed to represent the deviation of a subject's gait from the unimpaired population.
2) Both the Reference and the Able-Bodied Groups are representative samples of this population, and as such should exhibit the same NI.
3) The difference in NI between the Reference and Able-Bodied Groups provides an estimate of the smallest deviations that can be reliably attributed to pathology, rather than to natural variations in gait or shortcomings in the NI methodology.

Idiopathic toe-walkers and subjects with CP formed the Pathological Group (Table 1). These subjects were recruited from the Department of Paediatric Orthopaedics of the 'V. Buzzi' Children's Hospital in Milan. The same medical team selected all of the subjects in the Pathological Group. Unlike the approach of Schutte et al. [1], a distinction was made between the pathological subjects who were able to walk independently (independent ambulators) and those who required assistive devices such as crutches, a tripod, or the support

Table 1
Subjects included in the study

	Subjects analysed	Number
Independent ambulators	Able-Bodied	12
	Idiopathic toe-walkers	5
	Hemiplegics	27
	Diplegics	92
	Quadriplegics	7
Dependent ambulators	Diplegics	12
	Quadriplegics	6

of a relative (dependent ambulators). This distinction was considered important since the use of assistive devices has a significant influence on the subject's locomotor strategy. The current analysis, which also included subjects defined as idiopathic toe-walkers, considered a larger number of pathological subjects than did that of Schutte et al.[1].

In the Able-Bodied Group, the two trials deemed most typical were selected (1-left, 1-right), and a mean NI was obtained. The same procedure was followed in the Pathological Group. Mean values and ranges were obtained for the different diagnostic categories within the Pathological Group (Idiopathic Toe-Walking, Hemiplegia, Diplegia, Quadriplegia). In the Hemiplegic subjects, mean values for the plegic and the uninvolved limb were reported separately. The data for the Pathological Group were compared with those of both the Reference Group and the Able-Bodied Group.

Independent samples *t*-tests were used to check for pair-wise differences between group mean NI values ($P = 0.05$ for significance). The NI values for the Diplegic Group were not normally distributed, so a Mann-Whitney *U*-test was used when comparisons were made to this group ($P = 0.05$ for significance). Finally, the Jonkheere-Terpsta test was used to determine whether or not the NI ranked the groups of subjects by increasing pathology. The null hypothesis for this test was that the group mean NI values were all equal. The alternative hypothesis was that the group mean NI were ordered as follows (from lowest to highest): Reference, Idiopathic Toe-walking, Hemiplegia, Diplegia, Quadriplegia, Dependent. A significance level of $\alpha = 0.05$ was chosen for rejection of the null hypothesis.

3. Results

The mean values and standard deviations of the 16 parameters used to calculate the NI in the Reference Group are shown in Table 2.

The distribution of NI for the Reference Group subjects closely resembled a χ^2 distribution with 15 degrees of freedom (Fig. 1). The mean NI for the group was 16.4. The mean value for the normal group in the study of Schutte et al. [1] was 15.7. The distributions of NI in the current study and Schutte et al.'s study were similar.

The mean NI of the Able-Bodied Group (28.5) exceeded the mean NI of the Reference Group (16.4) (Fig. 2). The relatively small difference ($\Delta = 12.1$) was statistically significant at the $P < 0.05$ level.

The NI for all subjects (Reference Group, Pathological Group, and Able-Bodied Group) were compared to one another (Table 3, Fig. 3). The mean NI of the Idiopathic Toe-Walking Group (61.2) was higher than that of the Able-Bodied and Reference Groups, but was smaller than the mean NI value for subjects affected by any CP sub-types. Higher degrees of severity of CP-induced impairment were associated with higher NI values (group means). As noted earlier, the mean NI of the Able-Bodied Group was higher than that of the Reference Group, but still substantially lower than the mean NI of the Pathological Group. There was an overlap in NI values for subjects in the various CP sub-types. This reflects the range of gait and functional abilities that exist between subjects with the same CP sub-type. It was particularly interesting to note that subjects who required assistive devices for walking exhibited the highest NI.

Group mean differences were tested for statistical significance (Table 4) and the various subject categories differed significantly from one another. The only inter-group comparison that did not reveal a statistically significant difference was between diplegics and quadriplegics. This lack of statistical significance could be partly due to the considerable difference in the sizes of the two groups. The difference between the plegic and uninvolved limb of the hemiplegic group was not statistically significant, though a trend did exist ($P = 0.055$). The Jonkheere-Terpsta test showed that the

Table 2
Parameters included in the NI

Parameter	Mean		Standard deviation	
	Present study	Schutte et al.	Present study	Schutte et al.
Time of toe off (% gait cycle)	58.36	61.87	1.96	2.67
Walking speed/leg length	1.63	1.43	0.13	0.21
Cadence (step/sec)	1.91	1.94	0.31	0.11
Mean pelvic tilt (°)	9.43	9.26	5.20	4.26
Range of pelvic tilt (°)	3.81	3.57	1.25	1.60
Mean pelvic rotation (°)	−0.78	0.15	3.19	2.51
Minimum hip flexion (°)	−6.59	−11.14	6.00	6.75
Range of hip flexion (°)	38.98	45.00	4.24	5.15
Peak abduction in swing (°)	−0.16	−0.30	3.53	3.27
Mean hip rotation in stance (°)	2.03	10.91	8.98	7.33
Knee flexion at Initial Contact (°)	6.24	6.83	4.54	4.69
Time of peak flexion (% gait cycle)	70.06	71.40	1.85	2.70
Range of knee flexion (°)	56.34	54.44	4.60	10.59
Peak dorsiflexion in stance (°)	11.68	13.31	3.76	6.45
Peak dorsiflexion in swing (°)	3.82	3.21	4.08	4.88
Mean foot progression angle in stance (°)	−11.26	−9.76	6.50	6.46

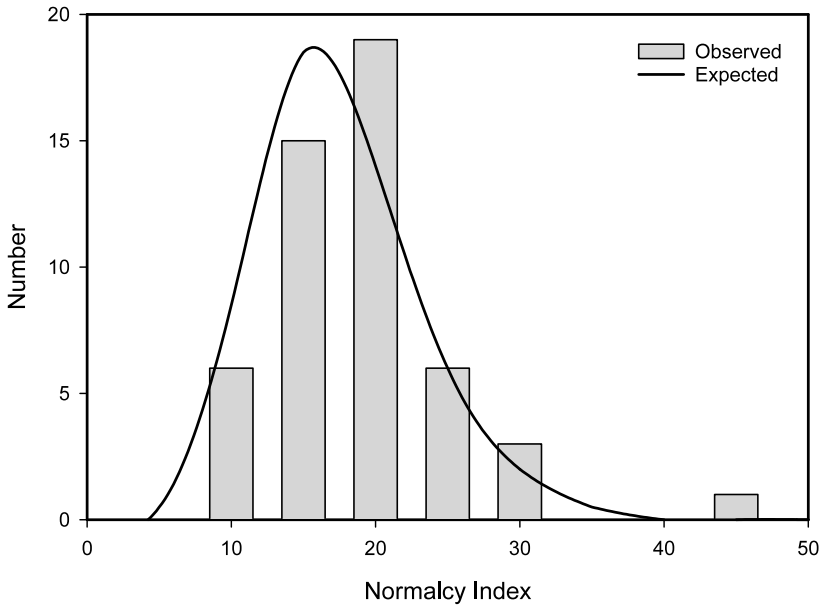

Fig. 1. Comparison of the observed and expected NI distributions. The distribution of NI for the Reference Group (bars) is compared to a χ^2 distribution with 15 degrees of freedom (the expected distribution). The two distributions are similar, verifying the implementation of the NI procedure.

Table 3
Group NI values

Group	*N*	Mean NI[a] (range)	Mean uninvolved (range)	Mean plegic (range)
Reference	25	16.36 (6.85–29.27)		
Able-Bodied	12	28.47 (7.44–46.32)		
Idiopathic Toe-Walkers	5	61.22 (44.7–82.1)		
Hemiplegics	27	189.28 (41.5–435.5)	177.38 (18.93–449.3)	201.17 (26.5–523.1)
Diplegics	92	278.12 (59.6–789.5)		
Quadriplegics	7	383.71 (177.4–626.5)		
Dependent Ambulators (Diplegic and Quadriplegic)	18	757.57 (306.8–1827)		

[a] Average of right and left sides.

Table 4
Post-hoc comparisons

Group I	Group II	Difference	*P*-value
Reference	Able-Bodied	12.1	<0.05
Able-Bodied	Idiopathic Toe-Walking	32.8	<0.05
Toe-Walkers	Hemiplegia	126.9	<0.05
Hemiplegia: Plegic limb	Hemiplegia: Uninvolved limb	25.8	0.055
Hemiplegia	Diplegia	90.0	<0.05[a]
Diplegia	Quadriplegia	105.6	0.11[a]
Independent Ambulator (Diplegia and Quadriplegia)	Dependent Ambulator (Diplegia and Quadriplegia)	467	<0.05

[a] Mann-Whitney *U*-test was used for pairs that included the Diplegia Group.

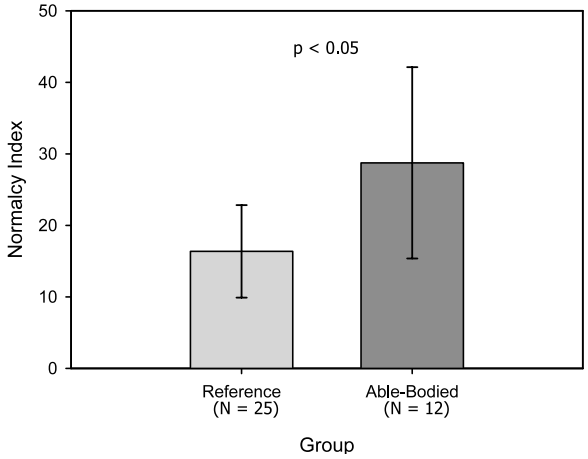

Fig. 2. Comparison of the Reference and Able-Bodied Groups. The group means and standard deviations are shown. A small, but statistically significant difference exists. Both groups are representative samples of the underlying unimpaired population. The existence of a difference suggests a lower bound for meaningful changes in NI of 12.

group mean NI were ranked according to increasing pathology ($J^* = 13.8$).

An important finding related to independent and dependent ambulation emerged, and was confirmed by the statistical analysis. The data demonstrated that dependent ambulation resulted in a significantly higher NI than independent ambulation, and that the NI for dependent ambulation was not related to the degree of clinical involvement. Patients who required walking aids tended to be more involved, but the NI was unable to distinguish the precise level of involvement in these patients.

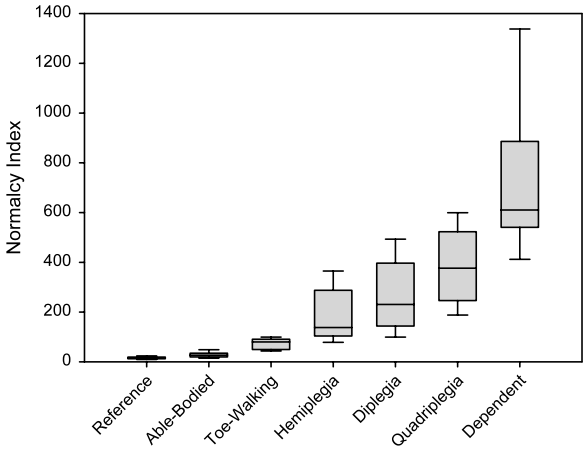

Fig. 3. Group NI distributions. The boxes show the 25th, 75th percentiles for the NI in each group; the whiskers show the 10th and 90th percentiles. The solid line is the group median. Clinical involvement increases from left to right. The group mean/median NI increase in accordance with clinical involvement, as confirmed by the Jonkheere-Terpsta test. This indicates that, on a group basis, the NI can distinguish between diagnoses. The range of NI values in a given group reflect the range of involvement for a given diagnosis, from mild to severe. The overlap between groups implies that an individual with a given NI could come from one of several different diagnoses. Thus, the NI cannot be used as a diagnostic tool, except for assessing the relative severity of a diagnosis that has already been established.

4. Discussion

The 16 kinematic parameters of the Reference Group subjects were consistent with data from the available Refs. [12,13] and with the corresponding values reported by Schutte et al. [1]. This resulted in the expected distribution of NI values for the Reference Group. The NI values of the Able-Bodied Group subjects were slightly higher than those of the Reference Group subjects, despite both comprising unimpaired subjects. This difference, however, was small compared to the differences between Reference Group and groups consisting of subjects with pathology. The difference between the two unimpaired groups arose from natural variation in gait, suggesting that NI changes of 12 or less are not significant. It is noteworthy that the NI for the Idiopathic Toe-Walking Group, a mildly involved group not considered in the original NI study, differed significantly from the NI of the Able-Bodied Group (Table 4). This demonstrates that the NI is also able to distinguish between unimpaired subjects and subjects affected by mild forms of pathology.

In hemiplegic subjects, the NI of the plegic limb was higher than that of the uninvolved limb, although the difference was not statistically significant (Table 4). Both limbs, however, had NI values significantly higher than the NI of the average Able-Bodied or Reference limb. This supports the widely understood clinical finding that hemiplegic subjects use their uninvolved limb to compensate for the pathological state of the plegic limb. The uninvolved limb, therefore, does not achieve a pathology free gait pattern, calling into question the label ‘uninvolved’.

There was a large range of NI values among independent ambulators with diplegia (Table 3). It was impossible to trace a uniform locomotor pattern in these subjects. A wide variety of terms have been proposed in the literature to describe the various patterns adopted by diplegics (for example crouch gait, jump knee gait, stiff knee gait, recurvatum knee) [16,17]. It therefore is logical that this category of subjects should, as was found in this study, present widely differing NI values.

Given the range of values for a diagnostic category, an individual’s NI can be used to assess their relative impairment; a task commonly undertaken using qualitative means. For example a patient with spastic diplegia, who presents with an NI of 129, would be two standard deviations below the mean for their diagnosis. They could therefore be categorized as having mild gait pathology relative to their diagnostic peers. On the other hand, an idiopathic toe-walker with a slightly lower NI (122) would be considered to have a severely impaired gait (plus two standard deviations) compared to other idiopathic toe-walkers. This categorical typing is often used in treatment planning,

outcome assessment and grouping of subjects in research studies.

The mean NI of dependent ambulators was significantly higher than that of independent ambulators. However, the NI for dependent ambulators did not correspond well with clinically diagnosed pathology. Based on the limited sample size in this study, it appears that the NI cannot distinguish diagnostic groups for dependent ambulators. As a result, the NI must be viewed as having significantly less value as an indicator of pathology in subjects who require walking aids.

The NI is robust enough to categorize pathology, ranging from mild disorders to quadriplegia. Since the NI is derived from gait data, it is susceptible to the same sources of error that are inherent to clinical GA (e.g. soft tissue artifact, marker misplacement). The principal component method, which is used to derive the NI, assigns weighting factors that are inversely proportional to the amount of variation exhibited by each gait measure in the unimpaired population. The method thereby provides a rational and objective scheme by which the most consistently measured gait parameters have the greatest influence. This ensures that neither natural variation nor experimental errors contribute excessively to the index.

Schutte et al. [1] opted to use only kinematic variables, to be able to include subjects who walked with the use of aids. Despite this consideration, the present study indicates that the gait pathology of non-independent walkers is not well characterized by the NI. This suggests that the NI could be modified to include kinetic variables, such as moments and power. Such an adaptation could potentially render a more complete and accurate evaluation of gait. Schutte et al. [1] emphasized that their choice of variables was not absolute and suggested that alternative sets of variables, appropriate to the subjects and activities under examination, should be considered. Future applications and adaptations of the NI are likely to reveal important insights in the analysis and treatment of movement disorders.

5. Conclusion

The NI is a simple yet meaningful indicator of gait pathology for independent ambulators and is a useful element in the evaluation of subjects with movement disorders. The NI is, for the purposes of most clinical investigations, independent of the laboratory in which the GA data are gathered. The NI thus appears to be an excellent tool for the evaluation and comparison of data between clinical research groups.

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