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Fuzzy logic for characterizing the moderate intensity of physical activity in children

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ABSTRACT

Objectives: The aim of this study was to better characterize the moderate intensity of PA among children by applying fuzzy logic as the most appropriate analytical approach. In this perspective, the 6-MWT was selected as a pertinent exercise modality, which covers as a whole, this intensity level.
Design: Methodological study.
Methods: Fuzzy logic was applied to accelerometer output obtained on 46 children aged 9–11 years. A fuzzy subset *A* was defined from the reference set *E* using a membership function (degree of truth). To adequately tap the moderate PA, a core of $\bar{X} \pm \sigma$ and a support of $\bar{X} \pm 2\sigma$ (with $\bar{X}$ the mean, and σ the standard deviation of the distribution) were selected.
Results: The walking speed during the exercise averaged $6.1 \pm 0.6\,\text{km}\,\text{h}^{-1}$ and the mean HR was 135 ± 14 bpm. The movement count (419 ± 127 to 433 ± 148 counts) exhibited no significant changes during the test. A value of 260 counts per 5-s (i.e., 3120 cpm) had equally 50% of degree of truth to encompass both "light" and "moderate" intensities of PA. Results suggest that the cut-point of >2296 cpm covers a low PA at 100% and a moderate PA at 0%.
Conclusions: Fuzzy logic provides a robust basis to processing accelerometer data, and brings a reliable solution to the concern about the in-between of PA intensities. Its application to calibration studies should not support the use of a cut-point of about 2000 cpm in children, and linguistic variables should now be preferred to numbered data in defining PA intensities.

1. Introduction

For their health and well-being, people are encouraged to participate in a physical activity (PA) of at least a "moderate" intensity (MI) on a daily basis.[1] However, in children and youth, the estimation of the MI seems challenging, as exemplified by heterogeneous and discrepant results released when using one or another cut-point to define this intensity level.[2] This confusion was once again displayed through the inability of a recent systematic review to provide a clear message on the adherence of children to PA guidelines.[3]

Many reasons can explain this inconsistency. Some of them are physiologically-based (e.g., the application of adults' metabolic equivalence to children)[4] and others relies on the biomechanical issues (e.g., the inappropriate selection of speeds during calibration tests). In this perspective, the spontaneous (i.e., comfortable) walking speed of children (6–17 years old) ranges between $3.8\,\text{km}\,\text{h}^{-1}$ and $4.5\,\text{km}\,\text{h}^{-1}$.[5,6] This speed range should elicit a heart rate (HR) of approximately 110–120 bpm in children, while HR >130 bpm should be expected in this age group at a MI, whatever the child's fitness level.[2] Furthermore, in calibration studies, there is also a great matter with the relevance of selected activities that are expected to catch children's pace to fit to the MI. On one side, activities such as brisk walking, bicycling, and active outdoor playing have been categorized as reaching this intensity level.[7] On the other hand, the 6-MWT is typically an exercise modality that portrays the characteristics of a moderate PA. By nature, the 6-MWT is a well calibrated and valid test[8] that is a self-paced running-free activity, close to daily living activities.[9] Thus, since the MI is so hard to figure out even among adults,[10,11] the use of the 6-MWT to teach MI to

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children and youth, and to calibrate accelerometers output for this intensity level is not unreasonable.

Just like MI, "light" and "vigorous" intensities are also difficult to disentangle. In fact, when engaged in a given PA, one important issue for researchers is to discern whether the intensity is "light", "moderate" or "vigorous". By definition, these intrinsic attributes to human movement are vague and overlap one another, so that it is absolutely hard to objectify where the "light" intensity ends, and when the "moderate" one begins. The question is raised about the appropriateness of probabilistic approaches to capture whether individuals are in one category or another one (i.e., light, moderate or vigorous level). For example, let us suppose an individual *i* who may have an 80% probability to be in a state of MI when engaged in a PA. This information must be interpreted as having an 80% chance of being in that state or to not be in that state at all. In the latter case, what can the PA level of this individual be? One might posit that there is an 80% chance of being strictly in a moderate PA, otherwise the PA level is strictly a low (or a vigorous) one. Here, we are left with poorly characterized position in-between PA intensities. This in-between state was recently referred to as the "zone of possible misclassification" (ZPM).[12]

The transition from a given intensity to another is a gradual and continuous process rather than a discrete phenomenon, by which the individual brutally "jumps" from one intensity to another. Thus, it seems necessary to address more precisely such a continuum in PA intensities. The use of fuzzy logic and especially linguistic variables may help in capturing the imprecise nature of these intensities. Fuzzy numbers provide a relevant measure of vagueness and may offer a better translation of the ZPM in PA. For instance, in the aforementioned case, in the framework of the fuzzy logic, our individual *i* would have been concomitantly up to 80% in a moderate-intensity PA and up to 20% in light intensity PA, which is closer to the reality. This is a different paradigm in comparison with the usual statistical and probabilistic approaches. Indeed, beyond the slight differences in the design of calibration studies, the most debatable thing is about their analytical methods. As stated by Trost et al.[13] regression-based cut-points continue to be the standard practice, though it is recognized that regression cannot accurately predict PA intensities.[14] Alternatively, the Receiver Operating Characteristics curve was applied. One weakness of this method is the choice of the dependent (or classification) variables (energy expenditure/VO_2; predefined types of activity; calibrated speeds) and the way it is further dichotomized to get the two classical values: presence [1] and absence [0]. Instead of setting a possibly inaccurate dichotomy, fuzzy logic is a many-valued logic, which takes into account of the continuum of truth-values to model linguistic vagueness of PA intensities.

The aim of this study was to better characterize the moderate intensity of PA among children by applying fuzzy logic as the most appropriate analytical approach. In this perspective, the 6-MWT was selected as a pertinent exercise modality, which covers as a whole, this intensity level.

2. Methods

Children from a public elementary school in Lille (France) were invited to participate in a project, which was approved by the local ethical board. The current study is a secondary analysis of data collected to examine the cardiac responses of overweight (vs. normalweight) children to the 6-MWT.[15] Prior to the beginning of the study, children and their parents provided written informed consent. Further details about the protocol can be found elsewhere.[15] Children were instructed to perform, under supervision one 6-MWT,[8] implemented during a school day in the playground between 08:30 am and 11:30 am. The total distance covered was calculated by multiplying the number of laps by 30 m and adding the additional meters in the final partial laps. The total distance walked (i.e., 6-MWD in meters) was rounded to the nearest meter. The walking speed ($\mathrm{m\,min^{-1}}$) of each child was calculated by dividing the 6 MWD (m) by 6 min.

Prior to the beginning of the 6-MWT, children were asked to sit at rest in a chair for a period of 5 min during which their resting heart rate (HR in bpm; Polar S810, Kempele, Finland) was measured. During the 6-MWT, HR was recorded every 5-s. Minute-to-minute HR during the test was calculated as well as the mean HR for the whole 6-min.

Devices such as accelerometers are considered as "gold-standard" to measuring free-living PA,[16] especially, the Actigraph accelerometer (Model 7164, Pensacola, FL), which was found to be the most validated activity monitor.[17] This accelerometer was used in the current study to evaluate movement counts during the test.

The Actigraph was tightly mounted at the right hip of each child before the beginning of the test. For the purpose of the experiment, the Actigraph was initialized to capture movement counts within 5-s time intervals. Minute-to-minute movement counts during the test were calculated by averaging counts obtained over the 1st, 2nd, 3rd, 4th, 5th, and 6th minute of the 6-MWT. The mean movement counts (MC) for the whole 6 min was also computed, and used as the main outcome of the study.

Because no distribution was skewed (Shapiro–Wilk test), comparisons according to gender were performed using an independent Student "*t*-test". An analysis of variance (ANOVA) for repeated measures was used to examine the course of HR and movement counts over the 6 min. The level of significance was set at $p < 0.05$. Statistical analyses were performed using PASW Statistics v.18 (IBM, SPSS Inc., Chicago, IL).

For an appropriate application of the fuzzy logic to data gathered from the 6-MWT, some important phases, including the definition of a fuzzy set, fuzzy numbers as well as the linguistic variable and modifiers, need to be fully considered. Contrary to inferential statistics, power calculation is not a pre-requisite for the use of fuzzy logic, even if this calculation has been performed in the primary analysis the current data.[15]

To design the fuzzy set and numbers, let us consider a reference set *E*, a fuzzy subset *A* from *E* is defined by a membership function μ_A in $\mathbb{R}$ such that $\mu_A \in [0, 1]$.[18,19] For a given fuzzy subset, it can be written:

$$\mu_A(x) = \begin{cases} 0 \text{ if } x \notin [a-\alpha, b+\beta] \\ 1 \text{ if } x \in [a, b] \\ 1 + \dfrac{x-a}{\alpha} \text{ if } x \in [a-\alpha, a] \\ 1 + \dfrac{b-x}{\beta} \text{ if } x \in [b, b+\beta] \end{cases} \quad (1)$$

with a core (*A*) such that $\mu_A(x) = 1$ if $x \in [a, b]$

and a

$$Support(A): \mu_A(x) \neq 0 \quad \text{if} \quad x \in [a-\alpha, b+\beta]$$

where $a - \alpha$ is the lowest extreme value of the fuzzy number, and $b + \beta$ the highest one.

Basically, variables take only a value in their belonging set. To the contrary, linguistic variables allow the modeling of imprecise values such as "this individual is tall" or even "the water is hot". These vague concepts, which are closer to our natural way of thought, are difficult to appraise using the traditional metric. However, they are readily computable in the framework of the fuzzy logic. A triplet (V, X, T_v) defines any given linguistic variable, as follows:

- *V*: Name of the variable (e.g., Height);