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生活習慣病予防や身体機能維持のためのエネルギー・たんぱく質必要量の
推定法に関する基盤的研究

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Ⅱ　分担研究者の報告書

子どもの推定エネルギー必要量のエビデンス収集を目的とする文献レビュー

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「日本人の食事摂取基準」において示される各種栄養素の基準値は，可能な限り科学的根拠に基づく策定を行うこととなっており，系統的レビューの手法を用いて，国内外の学術論文ならびに入手可能な学術資料を最大限に活用することを基本としている．本研究は，幼児の推定エネルギー必要量の策定根拠として利用可能な文献資料の収集とその精査を目的とした．

国際データベース（PubMed），国内データベース（医中誌 Web）を活用し，18歳までの年齢に限定して文献収集を行い，加えて，データベースに掲載されていない学術論文についても探索・収集した．

PubMed を活用したキーワード検索の結果，2008 年 1 月から 2013 年 2 月の期間に公表がなされ，幼児が対象に含まれている文献は 16 篇確認された．内容の精査を行ったところ，幼児ならびに幼児を含む対象者で，一日の総エネルギー消費量（TEE）と身体活動レベル（PAL）が共に掲載されている原著論文が 4 篇存在した．しかし，いずれの論文も 2010 年版レビューにおける算入基準を満たしてはいなかった．幼児の TEE のみを報告している文献としては，4 篇の原著論文が確認された．なお，日本人幼児・小児を対象に二重標識水（DLW）法を用いた研究は国際データベース上には確認されなかった．

国内データベースを用いた検索においても，過去 5 年間，日本人幼児または小児を対象に DLW 法を用いた研究論文は存在しなかったが，データベースに依存しない情報収集の結果，日本人低身長児（5.2±0.5 歳，8 名）を対象に実施された TEE と PAL の結果を含む論文が和文学術雑誌にて出版待ちであることが確認された．

幼児を対象に，実測 BMR から求められる PAL を報告する文献は新規に発見されなかった．このため，反映されるデータの数をエビデンスの強さと考えて基準値策定を行うのであれば，従来型の BMR×PAL から推定エネルギー必要量を求める方

法ではなく，例えば，体重あたりの TEE 基準値を示すアプローチの方が，特にデータの少ない幼児のエネルギー基準値策定の際には有効ではないかと考えられた.

A. 研究目的

エネルギーの食事摂取基準には，推定エネルギー必要量という概念が用いられており,「日本人の食事摂取基準」において，性別，年齢区分ごとの基準値が示されることで，各種フィールドにて適切な食事量を導き出すために活用されている.

推定エネルギー必要量は，可能な限り科学的根拠に基づいた策定を行うことを基本としており，系統的レビューの手法を用いて，国内外の学術論文ならびに入手可能な学術資料を最大限に活用することを基本としている．このため，日本人のデータが十分に存在しない場合には，当該分野の先進諸国の基準値を睨みつつ，これらを構築しているエビデンスを採用して策定が行われている.

幼児から成人，高齢者まで示される推定エネルギー必要量は，対象者の性別・年齢・体格要因を加味するための基礎代謝量（BMR）と身体活動量の指数である身体活動レベル（Physical activity level: PAL）の積によって求められている．このため，推定エネルギー必要量を導き出すためには，BMR と PAL のそれぞれについて，性別，年齢区分ごとの代表値を決めるためのエビデンスが必要となる．PAL については，日常生活中のエネルギー消費量の 0 正確な測定を実現する二重標識水（DLW）法によって求められる一日の総エネルギー消費量（TEE）を，同一被検者で測定された BMR で除した値がエビデンスとされている.

しかしながら，子ども，特に 5 歳未満の幼児については，日本人に限定せずとも実測データが十分に存在しない問題がある．2010 年版の策定に向けてワーキンググループが発足した 2008 年 9 月の時点で実施された子どもの PAL に関するシステマティックレビューでは，子どもの PAL のエビデンスを構成する文献，32 報の内，日本人の小児を対象とする論文はわずか1報のみであった．さらに幼児については，日本人を対象として測定された PAL のデータは存在せず，欧米人の基準値と同一のエビデンスにて PAL の代表値を決定せざるを得なかった．幼児については，世界的にもデータが希少で，5 歳未満については，DLW 法で TEE を求めつつ BMR の実測データを報告する論文が存在せず，BMR の推定値を用いて便宜的に PAL を算出したデータも許容する形で基準値を示す事となった.

本研究では，『日本人の食事摂取基準 2010 年版』の公表以降に報告された論文を文献データベースで検索することで幼児の推定エネルギー必要量をより強固なものとするためのエビデンスとなり得るデータを収集することを目的とした．また，可能な限りエビデンスを増やすため，国内研究者のネットワークを駆使してデータベースに掲載されていない情報についても収集を行うこととした.

B. 情報収集の方法

1．国際データベース

文献データベース『PubMed』を用いて，"DLW or (doubl* label* water)"をキーワー

ドに検索を行い，フィルター機能を用いて“Child: birth-18 years”に検索結果を限定した.

2．国内データベース

和文で公表された文献ならびに日本人を調査の対象としている文献を探し出す目的で，国内医学論文情報のインターネット検索サービスである『医中誌 Web』を活用し“二重標識水”ならびに“基礎代謝”をキーワードに検索を行い，アブストラクトを精査することで関連文献を探索した.

3．その他の方法

国内の DLW ユーザーネットワークを足がかりに，日本人小児を対象とした調査でありながら，データベース検索でヒットしない文献ならびに公表待ちとなっている論文についての情報収集を行った.

C. 研究結果

1．国際データベース

検索の結果，2008 年 1 月から 2013 年 2 月（最終検索日：2013 年 5 月 10 日）の期間に公表がなされた 18 歳以下の小児を対象とした文献は，69 篇であった．さらに，PubMed のフィルター機能（Preschool Child:2-5 years）を用いて，そのうち幼児が対象に含まれている文献 16 篇について内容を精査した.

日常生活を行っている幼児（被検者 5 名以上）の TEE ならびに PAL のデータが共に掲載されている論文は 4 篇存在した. Corder ら（2009）による原著論文は，TEE（6535±1114 kJ/day）に加え，安静時エネルギー消費量（REE）から求められた PAL［1.67±0.2(SD)］のデータを包含している（4.9±0.7 歳，4-5 歳の 27 名）．しかしながら，REE の測定条件は食後 2 時間，事前の仰臥位安静 10 分と BMR とはみなせない. Ojiambo ら（2012）の原著論文は，ヨーロッパ 4 カ国の幼児と小学生 49 名（6.9±1.5 歳，4-10 歳）を対象として TEE（6.6±1.2 MJ/day）と PAL（1.5±0.1，範囲：1.2-1.8）を報告している．しかし，PAL の分母である BMR は Schofield（1985）の推定式により算出されている．なお，本論文は先に公表された Bammann ら（2011）の原著論文に掲載された一部データを 2 次利用しているが，TEE と PAL については共用されていない.

1 篇の原著論文が過去の論文データ（Rush et al., 2003）の 2 次利用により幼児と小児の混成集団の TEE と PAL を報告している（Rush et al., 2010）．過去の報告と比較しても，男子 51 名，女子 40 名と例数は多いが，複数の人種をひとまとめとした解析を行っている．また，当該グループの 2003 年の報告については，REE の測定をランチの 1-3 時間経過後に行っているため，2010 年版においてエビデンスとして採択されていない.

2010 年版レビューにおける幼児・小児のデータの算入基準としては，PAL の分母として BMR の実測値が条件と定められ，そのようなデータが存在しない 5 歳未満についてのみ推定 BMR を許容するものであった．この条件と照らし合わせた場合，上記 3 篇のデータは，いずれも採択されないことになる.

なお，Butte ら（2010）の原著論文では，TEE（2153±625 kcal/day）と PAL

（1.54±0.16，範囲：1.30-2.08）が報告されており，BMRの測定条件もクリアしているものの，5歳から18歳までを総計したデータであるため，幼児のデータとして採択するのは難しい．

この他，幼児のTEEを報告している文献として，4篇の原著論文が確認された（Jackson et al., 2009; Djafarian et al., 2010; Walker et al., 2012; Collins et al., 2013）．また，検索結果には乳児を対象にTEEを測定した原著論文も1篇含まれていた（Gondolf et al., 2012）．

国際データベースで検索可能な文献には，日本人幼児・小児を対象にDLW法を用いた研究は確認されなかった．

2．国内データベース

ヒットした件数が少ないことから，アブストラクトから関連文献の探索を行ったが，日本人幼児または小児を対象にDLW法を用いた新規の研究論文の該当はなかった．

一方，日本人幼児のREEを測定した研究2篇が確認された．Nishimotoら（2012）は，フード法を用いて低身長児のREEに着目した研究を実施し，健常児対照群（6.3±2.2歳，男子6名，女子7名の計13名）の値も同時に報告している．もう1篇（Shimizu-Fujiwara et al., 2012）は，疾患児を対象として実施された調査であり，エネルギー必要量策定のエビデンスとすることは難しい．

なお，2007年にHikiharaらがInternational Journal of Sport and Health Scienceに発表した原著論文は，スポーツ選手群と年齢を一致させた非トレーニング群のTEEと実測BMRから求められたPALを報告している．非トレーニング群（8名）の年齢は18.6±0.5歳であり，小児もしくは成人のエビデンスとして採択できる可能性がある．

3．その他の方法

ここまでに実施したデータベース検索でヒットしない文献であるが，山田ら（2012，京都滋賀体育学研究）の和文原著論文では，陸上競技部に所属する小・中学生（12.3±0.6歳，男子7名，女子5名の計12名）を対象に，DLW法で求められたTEEが報告されている．

査読審査が完了し，公表待ちとなっている論文に関する情報収集も行った．大阪府立母子健康総合医療センターのグループによる，日本人低身長児（5.2±0.5歳，男子4名，女子4名の計8名）を対象に，TEEをDLW法，BMRをフード法で実測することでPALを取得した論文が日本栄養・食糧学会誌への掲載が決定している．

D．考察

DLW法でTEEを調査した研究のうち，国内外を問わず幼児のPAL，幼児を含んだPALを報告している研究は，直近の5年間においてわずか4篇にとどまった．しかも，厳密な観点から言えば，これらの報告は2010年版のシステマティックレビューの算入基準を満たしていない．例えば，Corderら（2009）の示したPALは，分母が条件の緩いREE（食後2時間経過後，仰臥位，事前安静10分間）であることから，過小評価されていることが懸念される．

DLW法については，幼児を対象とした場合においても正確度と精密度が保証されている一方で，ダグラスバッグ法やフード法に代表される間接熱量測定法については，成人を対象とす

る場合とは異なる困難さが存在する．このため，測定の対象である個体の真値が得られたと自信を持って判定することは容易ではない．即ち，幼児・小児を対象とした場合には早朝の空腹時に仰臥位覚醒状態で代謝測定を行う事自体が困難であり，測定手続が身体的・精神的な刺激となるため安静状態の保持も容易ではない．例えこれら視覚的に確認可能な問題点がクリアされた測定であっても，子どもの換気量は少なく，各種測定法が有する弱点に抵触せずに測定が完了できたと判断するには，事前・事後の慎重な検討が必要となる．

費用が掛かるうえ分析の難易度も高い DLW 法での TEE 測定に加え，正確な BMR の実測結果を期待する 2010 年版策定時のエビデンス算入基準は，かなり厳格なものであったが，採択できるデータ数が限定されることで，かえって不安定な基準値を生み出してしまっていた危険性は認識しなければならない．実際，2010 年版の策定から5年が経過したにもかかわらず，幼児の PAL の代表値を得るために採択できる文献は我々の確認した限り存在しなかった．

過去，DLW 法の普及期においては，年齢区分毎の TEE や PAL が記載された論文が数多く報告されていた．しかしながら，本研究を通じて検討された直近5年間の文献においては，1つの論文中に複数の年齢区分の代表値が示されるケースは，実に1例のみであり，比較的幅広い年齢の被検者らを1つの集団と捉えているケースが多く見られた．10 年程度時代を遡ると，DLW 法を利用した調査は新規性が高く，特定集団の TEE や PAL のデータのみでも原著論文となるだけの十分な価値が存在した．しかし，時代が進み，現在では研究目的を達成するための1つの測定法，測定値として位置づけられるに至っている．これが背景となり，幼児や小児を対象とする際には，測定が難しく，大きな労力が必要となる BMR や REE の測定は同時に行われなくなっているように見受けられる．今後，この傾向はより顕著になると思われ，PAL のエビデンスが増加しないことが懸念される．

これらを改善する目的で，特にエビデンスの限られている幼児においては，従来型の BMR を介して推定エネルギー必要量を得る方法ではなく，DLW 法で測定された TEE の結果に重きを置き，体重当たりのエネルギー必要量基準値を示す手法を採択した方が，背景となるエビデンスが増加することで，より安全な推定エネルギー必要量を示せる可能性があるのではないだろうか．特に 5 歳以下では PAL は「レベルⅡ（ふつう）」しか設定されておらず，身体活動量を考慮して策定されているとはいえない．今後この点については積極的な検討と議論が必要と思われる．また，日本人研究者にあっては，エビデンスが薄い幼児・小児を対象として，より積極的な調査を実施していく努力が求められるのは間違いない．

E. 研究発表

1．論文発表

なし

2．学会発表

なし

F. 知的財産権の出願・登録状況

なし

Ⅲ．研究成果の刊行に関する一覧表

書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書　籍　名	出版社名	出版地	出版年	ページ
なし							

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Hikihara Y, Tanaka S, Ohkawara K, Ishikawa-Takata K, Tabata I	Validation and comparison of three accelerometers for measurement of physical activity intensity during nonlocomotive activity and locomotive movement	J Physical Activity Health	9	935-943	2012
Ishikawa-Takata K, Kaneko K, Koizumi K, Ito C	Comparison of physical activity energy expenditure in Japanese adolescents assessed by EW4800P triaxial accelerometry and the doubly labeled water method	Br J Nutr	110	1347-1355	2013
Park J, Ishikawa-Takata K, Tanaka S, Hikihara Y, Ohkawara K, Watanabe S, Miyachi M, Morita A, Aiba N, Tabata I	The relationship of body composition to daily physical activity in free-living Japanese adult men	Br J Nutr	111	182-188	2014
Hikihara Y, Tanaka C, Oshima Y, Ohkawara, Ishikawa-Takata K, Tanaka S.	Prediction Models Discriminating between Nonlocomotive and Locomotive Activities in Children Using a Triaxial Accelerometer with a Gravity-removal Physical Activity Classification Algorithm	PLoS One	9	e94940	2014

Ⅳ. 研究成果の刊行物・別刷

Journal of Physical Activity and Health, 2012, 9, 935-943

Validation and Comparison of 3 Accelerometers for Measuring Physical Activity Intensity During Nonlocomotive Activities and Locomotive Movements

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Background: The current study evaluated the validity of 3 commercially-available accelerometers to assess metabolic equivalent values (METs) during 12 activities. ***Methods:*** Thirty-three men and thirty-two women were enrolled in this study. The subjects performed 5 nonlocomotive activities and 7 locomotive movements. The Douglas bag method was used to gather expired air. The subjects also wore 3 hip accelerometers, a Lifecorder uniaxial accelerometer (LC), and 2 triaxial accelerometers (ActivTracer, AT; Actimarker, AM). ***Results:*** For nonlocomotive activities, the LC largely underestimated METs for all activities (20.3%–55.6%) except for desk work. The AT overestimated METs for desk work (11.3%) and hanging clothes (11.7%), but underestimated for vacuuming (2.3%). The AM underestimated METs for all nonlocomotive activities (8.0%–19.4%) except for hanging clothes (overestimated by 16.7%). The AT and AM errors were significant, but much smaller than the LC errors (23.2% for desk work and –22.3 to –55.6% for the other activities). For locomotive movements, the 3 accelerometers significantly underestimated METs for all activities except for climbing down stairs. ***Conclusions:*** We conclude that there were significant differences for most activities in 3 accelerometers. However, the AT, which uses separate equations for nonlocomotive and locomotive activities, was more accurate for nonlocomotive activities than the LC.

Keywords: algorithm, metabolic equivalents, daily activity

It is well known that physical fitness and activity confer numerous health benefits in the prevention of lifestyle-related diseases.[1,2] Physical activity energy expenditure (PAEE) can be divided into exercise-related activity thermogenesis and nonexercise activity thermogenesis (NEAT), with the latter consisting mainly of energy expenditure (EE) of low-to-moderate intensity during lifestyle activities.[3] Levine et al suggested that the EE due to NEAT, including nonlocomotive activity, is much larger than EE due to exercise throughout the day and may be an important factor in the prevention of obesity.[4] Therefore, it is important to estimate EE of daily activities, including locomotive movements and nonlocomotive activities such as household tasks and occupational activities. As Westerterp indicates, PAEE of nonlocomotive activities accounts for more than 50% of total PAEE.[5]

Recently, various types of small and lightweight accelerometers have become available for assessing the amount and intensity of physical activity (PA). However, these devices use different algorithms, which depend on the number of axes (uni- or triaxial) and predictive equations for PAEE and intensity.[6] The usefulness of the Kenz Lifecorder EX (LC; SUZUKEN Co., Ltd., Nagoya, Japan), a uniaxial accelerometer widely used in Japan, for assessing PA intensity and PAEE during locomotive movements such as walking and jogging has been reported.[7,8] However, total energy expenditure (TEE) calculated from the LC data significantly underestimated by 20%–35% the TEE measured by the doubly labeled water method in Japanese men.[9,10] We speculate that the most important reason for this underestimation is related to the algorithm of the LC accelerometer, which was designed to assess PA intensity during ambulation. The LC device determines PA intensity from the frequency of steps and the degree of vertical acceleration.[11] However, if some PA such as household work does not involve a sufficient number of steps, the LC instrument may not be able to accurately assess PA intensity.

Triaxial accelerometers have also become popular devices for assessing PA intensity.[12–14] Nevertheless,

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Hendelman et al indicated that the regression equation used to predict metabolic equivalent (MET) values based on locomotive movements had a different slope and intercept compared with regression equation based on nonlocomotive activities.[12] Thus, when an equation based on locomotive movements is used to predict MET values for nonlocomotive activities and ambulation, there could be large prediction errors. Midorikawa et al tried to resolve this discrepancy by separating nonlocomotive activities from locomotive movements using the ratio of vertical to horizontal acceleration.[13] That approach contributed to a small difference between predicted EE for 10.5 h and EE measured with a metabolic chamber. As observed above, accelerometers are gradually being developed with new specific algorithms. To date, numerous epidemiological studies on physical activity have been performed. Some studies used several different types of accelerometers to assess PA.[15,16] Since each accelerometer has a specific algorithm for estimating PA, it is difficult to compare the results obtained from different accelerometers.[17]

The current study examined the validity of 3 commercially-available accelerometers to predict MET values focusing specifically on nonlocomotive activities in field conditions. The accelerometers included the LC device, a triaxial accelerometer that uses 2 separate regression equations for nonlocomotive and locomotive activities, and a triaxial accelerometer that uses a single regression equation for all activities. We believe that these discussions might help us understand data of various accelerometers accumulated in epidemiology.

Methods

Subjects

All subjects were recruited through public applications and had no physical impairments that could affect household and locomotion activities. All subjects were fully informed of the purpose of the study and written informed consent was obtained from all subjects before the beginning of the study. This study was conducted according to the guidelines of the Declaration of Helsinki, and all procedures involving human subjects were approved by the Ethical Committee of the National Institutes of Health and Nutrition.

Anthropometry

Body weight was measured to the nearest 0.1 kg using a digital balance, and height was measured on a stadiometer to the nearest 0.1 cm. Body mass index (kg/m^2) was calculated as body weight divided by the square of body height.

Instruments

Lifecorder EX (LC). The LC (size: 72.5 × 41.5 × 27.5 mm; mass: 60 g, including a battery) was worn on the hip with an attached belt. This device was a uniaxial accelerometer with a sampling interval of 32 Hz. The LC output was a PA intensity score that consisted of a scale from 0–9 (level 0: rest; level 0.5: micro activity; level 1–9: movement). The intensity of PA (level 1–9) was determined from the frequency of steps and the magnitude of vertical acceleration that was categorized into 4 parts with 4 thresholds [threshold 1 (TH1): 0.06 g, TH2: manufacturer's fixed values, TH3: manufacturer's fixed values, TH4: 1.96 g]. The LC device registered steps when the vertical acceleration signal exceeded the second threshold or when the gap between the pulses was ≤ 1.5 s.[7,11] An activity eliciting 3 acceleration signals during a 4-s sampling interval was recognized as PA, which caused the grade (level 1–9) to be computed. If this condition was not satisfied and vertical acceleration did not exceed TH2, activities were considered by the LC to be micro activities (level 0.5). The LC intensity data output (level 1–9) were entered into a previously published equation to predict the MET value.[7] The equation was as follows:

$$\text{MET} = 0.043 \times a^2 + 0.379 \times a + 1.361$$

where a is the LC intensity.

ActivTracer (AT). This device (AC-210; size: 48 × 67 × 16 mm; mass: 57 g; GMS Co., Ltd., Tokyo, Japan) is a triaxial accelerometer for detecting movement in 3 dimensions. It was able to obtain 3-dimensional accelerations every 4 s with a sensitivity of 2 mG and using a band-pass filter of 0.3–100 Hz. We calculated the synthetic accelerations from the following equation:

$$\text{Synthetic acceleration} = (x^2 + y^2 + z^2)^{0.5}$$

where x is anteroposterior acceleration, y is mediolateral acceleration and z is vertical acceleration. The synthetic acceleration was inserted into the formula reported by Midorikawa et al to calculate the physical activity ratio (PAR).[13] The PAR was then divided by 1.1 to convert it to a MET value because resting metabolic rate (RMR) in the sitting position without a meal was 1.1 times the basal metabolic rate (BMR) (RMR: 0.99 ± 0.177 kcal/min; BMR: 0.89 ± 0.19 kcal/min) in the current study. Although Midorikawa et al adapted their formula for sleeping metabolic rate (SMR; ie, average metabolic rate over an 8-h sleeping period),[13] we confirmed that SMR for adults was approximately equal to BMR.[18] The equations of Midorikawa et al were as follows[13]:

$$\text{PAR} = 0.0123 \times b + 1.7208 \text{ (House work)}$$

$$\text{PAR} = 0.0081 \times b + 0.9234 \text{ (Walk)}$$

$$\text{MET} = \text{PAR} / 1.1$$

where b is the synthetic acceleration in mG detected by the AT. Midorikawa et al reported that this device could differentiate the activity level from "housework" to "walk" based on the ratio of vertical to horizontal acceleration (housework < 0.750; walk > 0.751). Therefore, we followed this procedure and predicted MET values from these equations.[13]

Actimarker (AM). The AM (test model; size: 60 × 35 × 13 mm; mass: 24 g; Matsushita Electric Works, Ltd., Osaka, Japan) was another triaxial accelerometer. It obtained 3-dimensional acceleration every 12 s with a sensitivity of 40 mG at a sampling rate of 20 Hz. We calculated the synthetic acceleration from the following equation:

$$\text{Synthetic acceleration} = (X^2 + Y^2 + Z^2)^{0.5}$$

where X is anteroposterior acceleration, Y is vertical acceleration, and Z is mediolateral acceleration. A predictive equation was obtained from the relationship between 3-dimensional synthetic acceleration and oxygen uptake during sedentary to vigorous PA, including nonlocomotive activities and locomotive movements.[19–21] The following equations were used to convert 3-dimensional synthetic acceleration to EE:

$$\text{Kcal (min)} = c \times d \times \text{BMR (kcal/day)} + \text{RMR (kcal/min)}$$

$$\text{MET} = \text{kcal (min)} / \text{RMR (kcal/min)}$$

where c is the coefficient and d is synthetic acceleration. BMR was estimated using predicted body surface area (cm^2). BMR was calculated from body weight (kg), height (cm), sex, and age using a formula for the Japanese population standardized by multiplying by a standard value ($kcal/m^2/h$) corresponding to age (5th edition of Recommended Allowances Dietary Reference Intake in Japan).[22] Moreover, BMR (kcal/day) was multiplied by 1.2, which is the ratio of sitting RMR to BMR in AM and includes diet-induced thermogenesis, and then divided by 1440 min to estimate RMR per minute in the sitting position several hours after a meal.

Procedures

The subjects visited the laboratory early in the morning in a fasted state. After the study protocol was explained, anthropometric measurements were done. Next, they were asked to rest in the supine position for 30 min, and then BMR was measured in the supine position and RMR in the sitting position. The subjects performed 12 physical activities that included nonlocomotive activities such as desk work, vacuuming, hanging clothes, washing dishes, and moving a small load (5 kg), and locomotive activities such as climbing down stairs, climbing up stairs, slow walk (55 m/min), normal walk (70 m/min), brisk walk (100 m/min), walk with 3-kg baggage (70 m/min), and jogging [male (140 m/min), female (120 m/min)]. These activities were chosen as representative activities of daily life and were based on our preliminary 3-day observations in free-living conditions. The preliminary study was performed using the activity records of 93 subjects who lived in the Tokyo metropolitan area. MET values were measured during all activities. All subjects wore the AM on the right waist and the AT on the left waist symmetrically. Furthermore, the LC was placed diagonally forward right of the waist according to the instructions of the manufacturer. These accelerometers were tightly attached with a belt during each activity. According to our unpublished data, such a small difference in the position of placement does not systematically affect the results. Before the experiment started, the accelerometers were synchronized using a wave clock for reference.

Measurement of BMR and RMR

After we verified that the subjects had fasted, each subject was fitted with a facemask and breathed into a Douglas bag twice for 10 min; the bag concentrations of oxygen and carbon dioxide were analyzed by a mass spectrometer (ARCO-1000; Arco System Inc., Kashiwa, Japan). Oxygen consumption (VO_2) and carbon dioxide production (VCO_2) at rest and during activity were measured using the Douglas-bag method. Expired gas volume was measured using a certified dry gas meter (DC-5; Shinagawa Co., Ltd., Tokyo, Japan). EE was calculated from VO_2 and VCO_2 using Weir's equation[23]:

$$\text{EE (kcal)} = 3.9 \times VO_2 + 1.1 \times VCO_2.$$

Measurement of PA intensity

Measurement of each activity began after a preliminary period that was needed for subjects to reach a steady-state condition. The times needed to collect expired gas, which differed between activities, are shown in Table 1. The method for calculating the EE of each activity was the same as the method used for BMR and RMR. To calculate the MET value, EE during each activity was divided by the measured value of RMR.

Statistics

Statistical analysis was performed using JMP version 6.0 for Windows (SAS Institute, Tokyo, Japan). All results are shown as mean ± standard deviation (SD). Pearson's correlation coefficient was used to evaluate the relationships between variables. One-way analysis of variance (ANOVA) was used to compare measured and predicted MET values, and Tukey's HSD test was used for post hoc comparisons when the ANOVA was significant. Midorikawa's discriminative method was used to discriminate data produced by nonlocomotive activities from that produced by locomotive movements.[13] $P < .05$ was considered statistically significant.

Results

The participants were 33 men (age: 41.8 ± 14.0 years, height: 169.9 ± 6.2 cm, weight: 67.3 ± 14.1 kg, body mass index (BMI): 23.2 ± 3.9 kg/m^2) and 32 women (age: 43.1 ± 12.8 years, height: 158.0 ± 5.2 cm, weight: 55.6 ± 9.6 kg, BMI: 22.2 ± 3.5 kg/m^2).

We examined the effects of sex and age on measured MET values using a general linear model before statistical analysis because of the large age range of the subjects. As a result, there was no effect ($R^2 = .003$, $P = 0.23$) of age (F value = 2.35, $P = .13$) or sex (F value = 0.55, $P = .46$) on the measured MET values. Therefore, the relationships between measured and predicted PA intensities were examined without adjustment for age and sex.

Table 1 Duration for Measurement of Physical Activity Intensity

	Content of activity	Steady state (min)	Measurement of expired gas (min)
Desk work	Typewriting using personal computer with sitting in a chair	3.0	7.0
Vacuuming	Vacuuming clean in a room (about $17m^2$) while moving	3.0	3.0
Hanging clothes	Hanging out washing then and there	3.0	3.0
Washing dishes	Washing dishes with standing position	3.0	3.0
Moving a small load	Moving a small load (5kg) from one place to the other place (between about 3 meters), repeatedly	3.0	2.0
Climbing down stairs	Climbing down stairs according to the leader	2.0	1.0
Climbing up stairs	Climbing up stairs according to the leader	1.0*	0.8
Slow walk	Walk according to pace leader machine (55m/min) on ground	3.0	3.0
Normal walk	Walk according to pace leader machine (70m/min)on ground	3.0	2.0
Brisk walk	Walk according to pace leader machine (100m/min) on ground	3.0	2.0
Walk with a baggage	Walk with a baggage (3kg)according to pace leader machine (70m/min) on ground	3.0	2.0
Jogging	Jogging according to pace leader machine (male: 140m/min, female: 120m/min) on ground	3.0	1.0

* Average time; the measurement for climbing up stairs was performed with a very short interval after climbing down stairs.

The differences between predicted and measured MET values are shown in Figure 1 (nonlocomotive) and Figure 2 (locomotive). Predicted MET values of nonlocomotive activities estimated by the AT and AM moderately agreed with measured MET values, whereas the LC systematically underestimated measured MET values. In contrast to nonlocomotive activities, the 3 accelerometers tended to have similar validity for locomotive movements.

The percentage difference between predicted and measured MET values is shown in Table 2. In all nonlocomotive activities except desk work, MET values were significantly underestimated by 20.3%–55.6% using the LC data. Using the AT data, MET values were significantly underestimated by 11.0% for moving a small load and by 2.3% for vacuuming, whereas MET values were overestimated by 11.3% for desk work and 11.7% for hanging clothes. Using the AM data, the MET values during all activities except for hanging clothes (overestimated by 16.7%) were significantly underestimated by 8.0%–20.0%. Although MET values during locomotive movements except for climbing down stairs were significantly underestimated by all 3 accelerometers, there were no differences among the 3 devices with the exception that high-intensity PA such as jogging was underestimated more by the LC (25.7%) than by the 2 other devices.

We described the relationship between LC intensity and MET values in Figure 3. For nonlocomotive activities, the LC intensities were within a narrow range (0.5 to 1.5), in spite of the finding that the MET values during each activity were significantly different.

Table 3 indicates that the rate of walking evaluated by the LC device, which was calculated from dividing the total number of steps during each activity by the length of that activity period, was considerably less during nonlocomotive activities than during locomotive movements.

Discussion

The purpose of this study was to compare the validity of 3 accelerometers equipped with specific algorithms to measure PA intensity during nonlocomotive activities and locomotive movements.

Figure 1 and Figure 2 show the differences between predicted MET values and measured MET values. We found that the LC instrument had difficulty evaluating PA intensity during nonlocomotive activities (Figure 1, Table 2). One of the reasons for this is that the equations for the LC device were specific for walking and running on a treadmill in the laboratory.[7] In addition, although the LC intensity (output data) was determined from the number of steps and vertical acceleration, the steps per minute were considerably less in nonlocomotive activities than in locomotive movements (Table 3). The LC device registered movement when the vertical acceleration signal exceeded the second threshold or when the gap between pulses was ≤ 1.5 s.[7,11] Therefore, it is possible that most steps taken during nonlocomotive activities were not detected by the LC device because the acceleration signals were not regular but rather intermittent. For example, during vacuuming, the LC accelerometer could not detect movements because the interval between them was often > 1.5 s (Table 3). We confirmed that nonlocomotive activities such as vacuuming and moving a small load corresponded to LC intensities "0.5–1.5,"

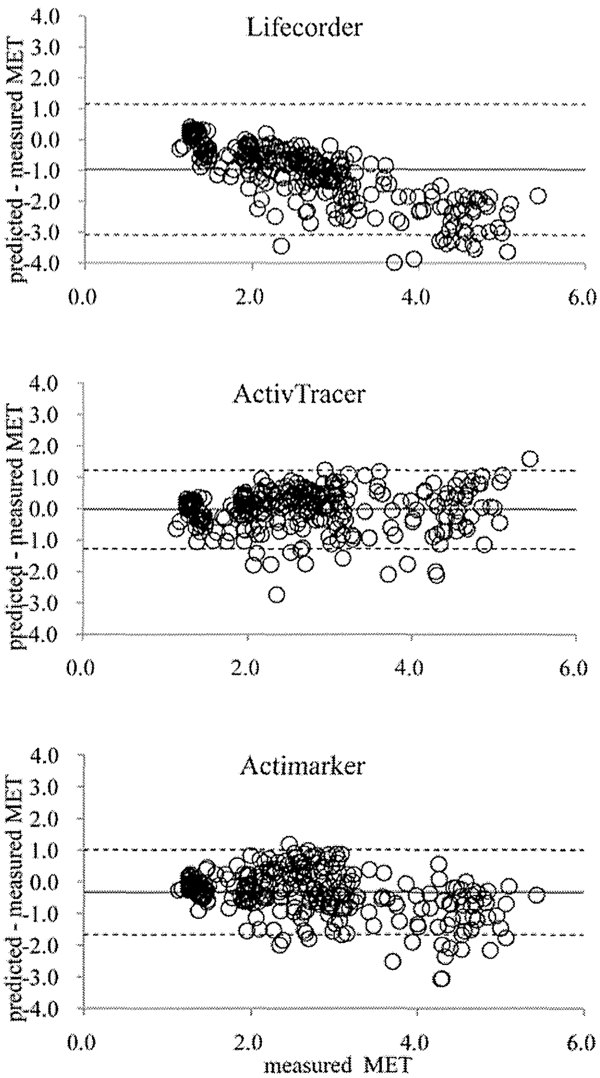

Figure 1 — Mean differences of each accelerometer between predicted and measured METs for nonlocomotive activities using Bland and Altman plots.

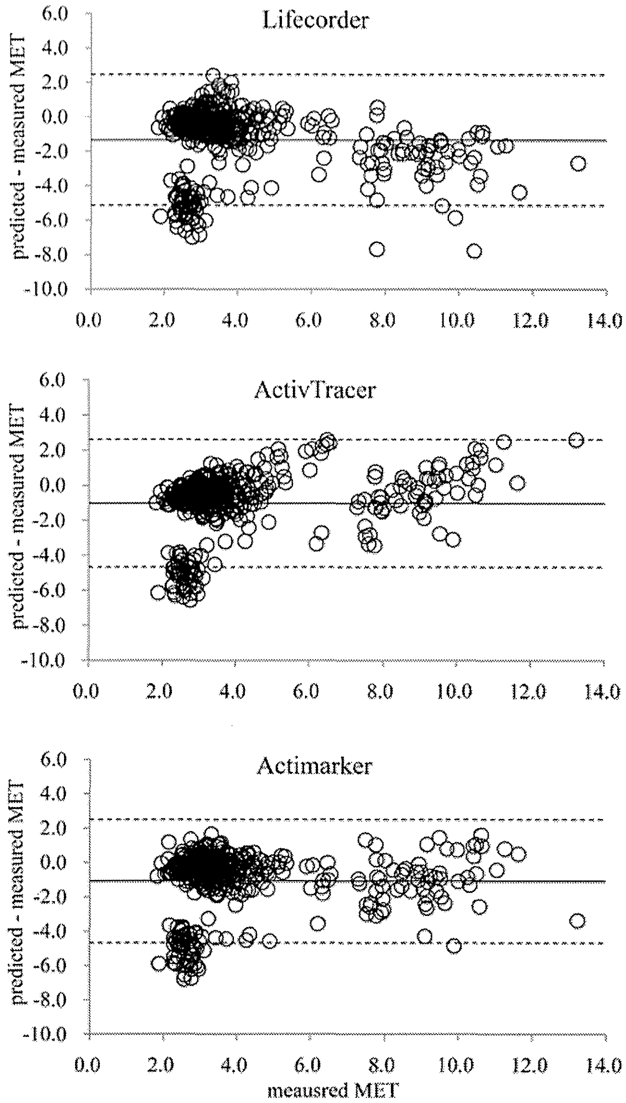

Figure 2 — Mean differences of each accelerometer between predicted and measured METs for locomotive movements using Bland and Altman plots.

even when these MET values were comparable to slow walk and normal walk (Figure 3).

In contrast, the differences between measured and predicted MET values obtained using AT and AM data were less than those obtained using LC data, although there were also significant differences between MET values by triaxial accelerometers and measure MET values for several nonlocomotive activities (Table 2). The predictive equations for the AT and AM devices were obtained for both locomotive movements and nonlocomotive activities.[13,21] This might explain why the differences between predicted and measured MET values were better with the AT and AM accelerometers compared with the LC accelerometer. Moreover, the AT equations tended to have better predictive ability than the AM equations because the suggested discrimination method of Midorikawa et al was applied for discriminating between the MET values of nonlocomotive activities and locomotive movements.[13] An advantage of the AT over other devices is that it can evaluate complex motions such as moving a small load, which consist of both types of activity like ambulatory movement, bending forward (unloading) and standing up (catching up load). However, since the AT as well as the other accelerometers could not detect the weight that an individual was carrying, it is not surprising that the MET values predicted by the AT underestimated the actual values by 11.0%.

Meanwhile, we confirmed that the accuracy of 3 accelerometers in locomotive movements was similar (Figure 2, Table 2). However, the underestimation of MET values for jogging was greater with the LC device than with the 2 other devices. Based on the original

Table 2 Percent of Differences Between Measured and Predicted METs

	Measured METs		Predicted METs: Lifecorder		Predicted METs: ActivTracer		Predicted METs: Actimarker		Percent of difference: Lifecorder		Percent of difference: ActivTracer		Percent of difference: Actimarker		Statistics	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*	Post hoc test
Desk work	1.1	0.1	1.4	0.0	1.3	0.0	1.0	0.1	23.2	7.9	11.3	7.9	–8.0	7.6	<0.0001	LC > AT > ME > AM
Vacuuming	2.9	0.7	1.6	0.0	2.7	0.4	2.3	0.3	–44.0	11.1	–2.3	24.9	–20.0	14.1	<0.0001	ME > AT > AM > LC
Hanging clothes	2.3	0.4	1.5	0.0	2.5	0.4	2.6	0.4	–32.6	10.6	11.7	21.8	16.7	20.4	<0.0001	AM,AT > ME > LC
Washing dishes	1.8	0.4	1.4	0.1	1.8	0.3	1.6	0.3	–20.3	13.5	0.2	23.6	–12.0	19.5	<0.0001	ME,AT > AM > LC
Moving a small load	4.4	0.7	1.9	0.1	4.2	0.6	3.5	0.3	–55.6	7.3	–11.0	7.3	–19.4	13.8	<0.0001	ME,AT > AM > LC
Climbing down stairs	3.2	0.5	3.4	0.8	3.0	0.4	3.3	0.4	9.6	30.3	–3.2	20.1	8.6	22.4	0.0003	LC,AM > AT
Climbing up stairs	7.6	0.8	2.5	0.3	2.8	0.5	2.7	0.3	–66.4	5.1	–63.8	8.0	–64.5	5.6	<0.0001	ME > AM,AT,LC
Slow walk	3.1	0.4	2.7	0.3	2.8	0.7	2.8	0.3	–12.7	13.2	–11.3	19.7	–9.0	12.8	<0.0001	ME > AT,AM,LC
Normal walk	3.6	0.5	3.2	0.4	3.3	0.7	3.3	0.3	–10.5	12.8	–7.3	20.4	–8.0	13.1	<0.0001	ME > AT,AM,LC
Brisk walk	4.6	0.7	4.0	0.5	4.2	0.7	4.0	0.6	–12.9	12.6	–9.1	18.3	–11.7	13.8	<0.0001	ME > AT,AM,LC
Walk with a baggage	4.2	0.6	3.5	0.5	3.7	0.8	3.6	0.4	–16.1	12.3	–12.8	20.3	–14.5	12.6	<0.0001	ME > AT,AM,LC
Jogging	9.5	1.1	6.8	1.5	9.0	1.3	8.1	1.8	–25.7	14.6	–4.0	14.8	–10.7	14.6	<0.0001	ME > AT < AM < LC

Abbreviations: ME; measured, LC; Lifecorder, AT; ActivTracer, AM; Actimarker.

Note. Post hoc test was adapted by Tukey's HSD test.

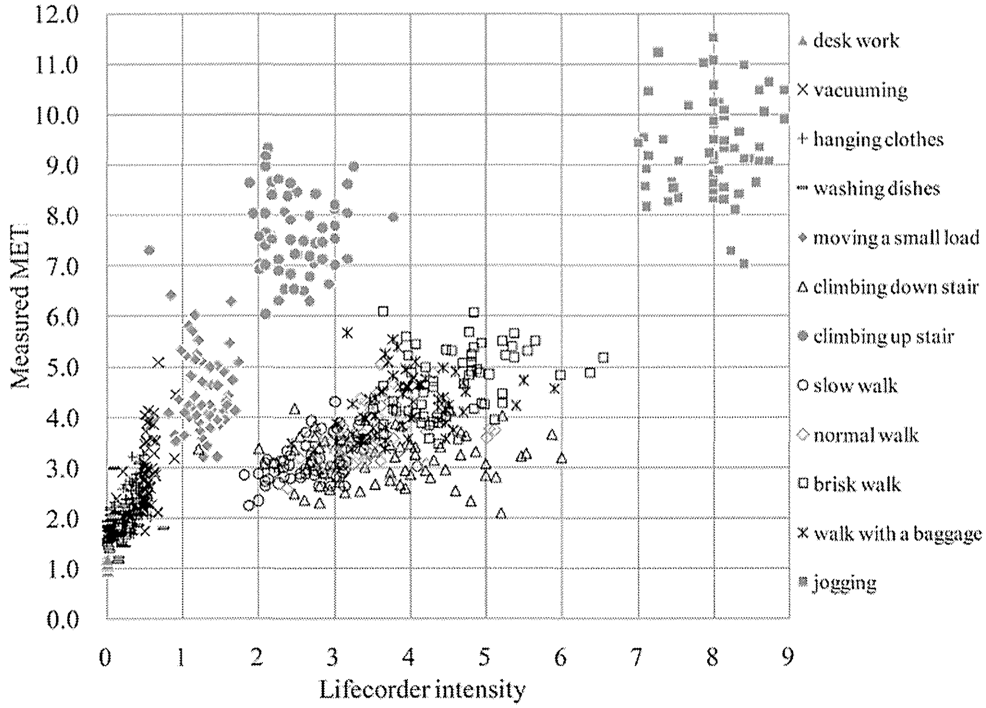

Figure 3 — Relationship between output data from Lifecorder and measured MET values.

Table 3 Rate of Steps for Each Activity*

	Rate of steps	
	Mean	**SD**
Desk work	0.0	0.0
Vacuuming	6.8	8.0
Hanging clothes	1.6	2.6
Washing dishes	0.3	1.6
Moving a small load	44.4	9.4
Climbing down stairs	104.1	14.6
Climbing up stairs	90.9	13.9
Slow walk	100.0	6.8
Normal walk	111.1	6.2
Brisk walk	121.0	6.8
Walk with a baggage	115.5	6.0
Jogging	161.0	25.5

* Rate of steps (frequency/minute) was calculated from dividing total steps during each activity by action time (minutes).

algorithm and equation, the LC can detect PA up to 8.3 MET values corresponding to a maximum LC intensity of "9".[7] Therefore, it would be difficult to evaluate jogging over 120–140 m/min using the LC, because jogging in this study corresponded to 9.5 MET values.

An important aspect of MET prediction by the 3 accelerometers is the measurement of RMR, and the error in RMR can affect the predicted MET values. The equation for the AT device predicts the physical activity ratio (PAR), which is the energy expenditure divided by the BMR. Therefore, the PAR was divided by 1.1 to convert it to a MET value in this study according to the Dietary Reference Intake in the US.[24] Actually, since the ratio of RMR to BMR in this study was 1.11 (see the Methods section), there was little effect of the RMR on the MET values predicted by the AT device. Furthermore, the LC equation depends on MET values calculated using 3.5 ml/kg/min as the RMR according to a previous report.[7] With the AM device, the estimated RMR was used (see the Methods section). We found that 3.5 ml/kg/min (LC) and the predicted RMR (AM) were about 8% higher than the actual RMR. Considering the difference of RMRs, it may raise the validity of this study by up to approximately 7% positively. However, even if the RMR differences slightly affected the predictive accuracies of the LC and AM accelerometers, we still found that there was a larger error for nonlocomotive activities than for locomotive movements.

An important issue that must be considered is whether the AT accelerometer evaluated in the current study is valid in obese individuals. With respect to this point, we previously reported the effect of body weight on MET values in the same subjects and during the same physical activities as in the current study.[25] Our previous report indicated that when the BW is more than 10 kg above average body weight (60.0 kg), there is about a +5% error for nonlocomotive activities (vacuuming) and +3% to 5% error for locomotive movements. Thus, MET values are associated with body weight to some degree. Therefore, when the results of this study are applied to obese individuals, the effect of body weight on MET values should be considered. However, significant correlations were not obtained between the predictive errors and body weight in this study except for climbing up stairs.

There are 2 limitations in this study. The primary limitation is whether the errors in predictive accuracy in the current study affect TEE in an entire day. To address this issue, it will be necessary to examine the validity using the doubly labeled water method under free-living conditions in a future study. However, Westerterp indicated that in a subject with an average physical activity level of 1.75, PAEE of nonlocomotive activities, which consist of sitting and standing without movement and standing active (ie, washing dishes), accounts for more than 50% of total PAEE.[5] Therefore, it may be possible that the difference in predictive ability among the AT, AM and LC devices in the current study affects the prediction of TEE. Furthermore, Leenders et al indicated that the predictive equations based on the relationship between acceleration and energy expenditure during locomotive movements led to underestimation of TEE by more than 10%, but the predictive equations based on both nonlocomotive activities and locomotive movements did not necessarily lead to TEE underestimation.[26] Considering these viewpoints, to improve the predictive ability for TEE, the predictive equation should be based on both nonlocomotive activities and locomotive movements.

Another limitation is that it is not easy to make generalizations regarding the currently used other accelerometers, because the aim of this study was to examine the validity of 3 commercially-available accelerometers that employ specific algorithms. However, few previous studies have attempted to validate PA intensity from commercially-available accelerometers data for both nonlocomotive activities and locomotive movements obtained under field conditions. Based on our results, we suggest that triaxial accelerometers based on nonlocomotive activities and locomotive movements have better accuracy than uniaxial accelerometer. In particular, triaxial accelerometer with equations that distinguish between nonlocomotive and locomotive movements might be more accurate. Meanwhile, the algorithm of LC could not evaluate nonlocomotive activities, which probably attributes to underestimation of PA in a whole day. We also believe that it gives full recognition to the significance of nonlocomotive activities (or NEAT). In addition, our results may help both researchers and general users understand how to use accelerometers to evaluate PA.

In conclusion, we didn't find a difference in predictive ability of 3 accelerometers for locomotive movements except for jogging. Meanwhile, we found that the MET values obtained during nonlocomotive activities by the LC device consistently underestimated the measured MET values. In contrast, the AT and AM devices more accurately assessed MET values during nonlocomotive activities, although there were still significant deviations from measured MET values. In particular, the reason why the AT device has better predictive ability for nonlocomotive activities is probably due to the use of separate predictive equations for both nonlocomotive activities and locomotive movements.

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Comparison of physical activity energy expenditure in Japanese adolescents assessed by EW4800P triaxial accelerometry and the doubly labelled water method

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Abstract

The present study compared the accuracy of triaxial accelerometry and the doubly labelled water (DLW) method for measuring physical activity (PA) in Japanese adolescents. A total of sixty adolescents aged 12–15 years were analysed. The total energy expenditure (TEE) was measured over 7 d by the DLW method and with an EW4800P triaxial accelerometer (Panasonic Corporation). The measured (RMR_m) and predicted RMR (RMR_p) were 5·7 (SD 0·9) and 6·0 (SD 1·0) MJ/d, respectively. TEE measured by the DLW method and accelerometry using RMR_m or RMR_p were 11·0 (SD 2·6), 10·3 (SD 1·9), and 10·7 (SD 2·1) MJ/d, respectively. The PA levels (PAL) measured by the DLW method using RMR_m or RMR_p were 1·97 (SD 0·31) and 1·94 (SD 0·31) in subjects who exercised, and 1·85 (SD 0·27) and 1·74 (SD 0·29) in subjects who did not exercise. The percentage of body fat correlated significantly with the percentage difference between RMR_m *v.* RMR_p, TEE, PA energy expenditure (PAEE) and PAL using RMR_p, and PAL using RMR_m assessed by the DLW method and accelerometry. The present data showed that while accelerometry estimated TEE accurately, it did not provide the precise measurement of PAEE and PAL. The error in accelerometry was attributed to the prediction error of RMR and assessment in exercise.

Key words: **Junior high school students: Total energy expenditure: Walking step counts: Sports**

Data from the Ministry of Education, Culture, Sports, Science, and Technology in Japan show that the proportion of obese (more than 120 % of standard body weight for height) Japanese junior high school students (aged 12–15 years old) is 9·37–10·99 % in boys and 7·89–8·92 % in girls, and that the proportion in boys has increased slightly over the last 20 years[1]. A change in physical activity (PA) may have effected this increase in the proportion of obesity, although data on PA in Japanese adolescents are limited.

The proportion of junior high school students participating in daily exercise increased from 1970 to 2000[2]. However, the PA level (PAL) and the amount of moderate-to-vigorous PA (MVPA) were not established in previous studies.

Studies of PA in Japanese adolescents often measured walking steps, as pedometers and accelerometers are very popular tools in Japan. These studies used uniaxial accelerometry to show that junior high school students walk 9450–15 428 steps/d on weekdays and 6375–15 517 steps/d on weekends[3]. Only two studies have measured total PA using the doubly labelled water (DLW) method in Japanese children and adolescents. Hikihara *et al.*[4] measured PA in high school baseball players (mean age 16·5 years, PAL 2·66), while Adachi *et al.*[5] measured PA in elementary school students (mean age 11·2 years, PAL 1·47). These studies simultaneously used uniaxial accelerometry, which is used widely in Japan. Hikihara *et al.*[4] reported that total energy expenditure (TEE) measured by uniaxial accelerometry correlated strongly with DLW data (r 0·73, $P<0·05$), but underestimated TEE (−35·3 (SD 3·6) %).

Subjective measurements are less preferable in children as a consequence of complex movement behaviour in young people and their inability to accurately recall the intensity, frequency and duration of activities[6]. Objective measurements using accelerometers are therefore required to evaluate PA[7,8]. Possible reasons for the limited data on PAL and MVPA in Japanese children are the lack of a validation

Abbreviations: ACC_m, measured by accelerometry using measured RMR; ACC_p, measured by accelerometry using predicted RMR; DLW, doubly labelled water; DLW_m, measured by the doubly-labelled water method using measured RMR; DLW_p, measured by the doubly-labelled water method using predicted RMR; TEE, total energy expenditure; MVPA, moderate-to-vigorous physical activity; PA, physical activity; PAEE, physical activity energy expenditure; PAL, physical activity level; r_{CO_2}, rate of CO_2 production; RMR_m, measured RMR; RMR_p, predicted RMR; TEE, total energy expenditure.

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study for accelerometry in children, and the higher cost of accelerometers compared with pedometers. Recently, Yamada *et al.*[9] found that a commercially available triaxial accelerometer (EW4800P; Panasonic Corporation) had relatively high accuracy for measuring PA in elderly Japanese subjects.

The objective of the present study was to evaluate the accuracy of EW4800P triaxial accelerometry for measuring PA in Japanese adolescents. This was achieved by comparing EW4800P data with PA measured by the DLW method.

Experimental methods

Participants

Subjects were recruited from one junior high school in Kanagawa Prefecture, near the Tokyo metropolitan area of Japan. Information on the study was sent to all students (*n* 300), and the purpose, methods and risks of the study were explained to students and their parents. No exclusion criteria were used in the recruitment of the subjects. A total of eighty students and their parents submitted written informed consent. Due to incorrect urine sampling, two subjects (one boy and one girl) were not included in the calculation of TEE by the DLW method. In addition, one subject was excluded, as she had a fever during the experiment. The periods when the accelerometer device was not worn were assessed from the accelerometer data and records kept by the students when the device was attached or removed. Valid days were defined as a non-wear time of less than five waking hours/d. In order for data to be used in the study, subjects had to wear the accelerometer for more than four weekdays and one weekend day. Of the subjects, nineteen were excluded because of faulty accelerometry data (for the two subjects described above, TEE data measured by both DLW and accelerometry were faulty). The remaining sixty subjects were included in the final analysis of the present study. The study was conducted according to the guidelines of the Declaration of Helsinki, and all procedures involving human subjects were approved by the Ethics Committee of Yokohama National University (three of the authors attended this university when the study was conducted).

Study schedule

Before the study period, anthropometric measurements, baseline urine sampling, dietary assessment and measurement of RMR (RMR_m) were performed. TEE was then measured over 1 week by the DLW method (TEE_{DLW}), with simultaneous collection of triaxial accelerometer data and completion of a simple PA record. The measurements were carried out from September 2006 to January 2007 depending on each student's schedule. Long vacations and periods of unusual PA, such as examination periods and special school events, were excluded from the experimental period.

Doubly labelled water method

After providing a baseline urine sample, a single dose of approximately 0·06 g/kg body weight ^2H_2O (99·8 atom%; Cambridge Isotope Laboratories) and 1·4 g/kg body weight $H_2{}^{18}O$ (10·0 atom%; Taiyo Nippon Sanso), was administered orally to each subject. Subjects were then asked to collect urine samples immediately after arriving at school at the same time every morning over 1 week. On Saturday and Sunday, subjects collected urine samples at home at the same time as on school days. All samples were stored frozen at −30°C in airtight parafilm-wrapped containers until analysis in our laboratory.

Gas samples for the isotope ratio mass spectrometer were prepared by equilibration of the urine sample with a gas. The gas used for equilibration of ^{18}O was CO_2 and H_2 was used for ^2H equilibration. A Pt catalyst (R1091830; Thermo Electron Corporation) was also used for the equilibration of ^2H. The urine samples were analysed in a DELTA Plus isotope ratio mass spectrometer (Thermo Electron Corporation). Each sample and the corresponding reference sample were analysed in duplicate. Throughout the analysis, average standard deviations were 0·5 ‰ for ^2H and 0·03 ‰ for ^{18}O.

The ^2H and ^{18}O zero-time intercepts and elimination rates (k_H and k_O) were calculated using least-squares linear regression of the natural logarithm of isotope concentration as a function of the time elapsed since dose administration. Zero-time intercepts were used to determine isotope pool sizes. The total body water was calculated as the mean value of the isotope pool size of ^2H (N_d) divided by 1·041 and that of ^{18}O (N_o) divided by 1·007. In the present study, N_d/N_o was 1·021 (SD 0·012) (range 1·000–1·055), which is within the recommended range for high-quality analysis[10]. The rate of CO_2 production (r_{CO2}) was calculated as:

$$r_{CO_2} = 0{\cdot}4554 \times TBW \times (1{\cdot}007k_o - 1{\cdot}041k_H),$$

where TBW is the total body water, and we assumed that isotope fractionation applied to both breath and transdermal water using equation (A6) from Schoeller *et al.*[11] with the revised dilution space constant of Racette *et al.*[12]. Calculation of TEE_{DLW} (kJ/d) was performed using a modification of Weir's formula based on the r_{CO2} and mean food quotient of the subjects in the study[13,14]. The food quotient was calculated based on dietary data from a brief self-administered dietary history questionnaire for junior high and high school students[15]. The intake of protein, fat and carbohydrate assessed from this questionnaire correlated with data obtained from dietary records, with Pearson's correlation coefficients ranging from 0·38 to 0·68[16]. The mean food quotient of subjects in the present study was 0·87 (SD 0·02), which is very similar to the values of 0·87 (SD 0·03) for Japanese adults[17] and 0·86 (SD 0·04) for elderly Japanese subjects[9]. TEE_{DLW} was expressed as mean TEE_{DLW} per d over the study period. However, we did not adjust TEE_{DLW} for the time at which the accelerometer was not worn, as the non-wear time was minimal in all the study subjects. PA energy expenditure (PAEE) was calculated as ($TEE_{DLW} \times 0{\cdot}9 - RMR$) using both RMR_m ($PAEE_{DLWm}$) and predicted RMR (RMR_p, $PAEE_{DLWp}$),

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assuming that dietary-induced thermogenesis accounted for 10 % of TEE_{DLW}. PAL was calculated as TEE_{DLW} divided by RMR_m or RMR_p (PAL_{DLWm}, PAL_{DLWp}). Fat-free mass was calculated as the proportion of water in fat-free mass and was determined to be 74·5 % for boys and 75·5 % for girls[18].

Triaxial accelerometry

A triaxial accelerometer (EW4800P; Panasonic Corporation) was secured at the waist by a rubber belt throughout the period of DLW measurements. Details on the accelerometer and its accuracy in elderly Japanese have been reported in a study by Yamada *et al.*[9]. The accelerometer measures 60 × 35 × 13 mm and weighs 24 g. It has a linear frequency response with a low-pass filter, and samples acceleration at 20 Hz with a range from zero to two times the acceleration of gravity. The device stores the standard deviation of the vector norm of the composite acceleration (*Km*) in three dimensions each minute as follows:

$$Km = \sqrt{\frac{1}{n-1}\left[\left(\sum_{i=0}^{n} X_i^2 + \sum_{i=0}^{n} y_i^2 + \sum_{i=0}^{n} z_i^2\right) - \frac{1}{n}\left\{\left(\sum_{i=0}^{n} x_i\right)^2 + \left(\sum_{i=0}^{n} y_i\right)^2 + \left(\sum_{i=0}^{n} z_i\right)^2\right\}\right]},$$

where n is the number of data for 1 min (n 1200), and Σx, Σy, and Σz are the sums of the acceleration in three directions over 1 min. Data were not rounded off for storage of *Km*.

Subjects were asked to wear the accelerometer for the whole day except when sleeping, bathing or swimming. If subjects took the accelerometer off due to difficulty in wearing it during contact sports, or if they forgot to attach it, they were asked to record the time of removal and the duration and type of PA carried out while not wearing the accelerometer. A commercially available accelerometry software (EW48001; Panasonic Corporation) was used to calculate the total energy expenditure measured by the accelerometer using RMR_p (TEE_{ACCp}), walking steps and duration of light PA (less than 3 metabolic equivalents), moderate PA (3–6 metabolic equivalents) and vigorous PA (6 metabolic equivalents or more). The metabolic equivalent intensity levels of physical activities were calculated using the simple linear regression of *Km* and O_2 consumption[19]. MVPA was calculated as the sum of moderate PA and vigorous PA. The commercially available software incorporated RMR_p calculated using standard values to calculate TEE_{ACCp} that were obtained for the Japanese population from the dietary reference intake in Japan[20]. PAEE assessed by accelerometry ($PAEE_{ACCp}$) was calculated as $TEE_{ACCp} \times 0{\cdot}9 - RMR_p$. PAL_{ACCp} was calculated as TEE_{ACCp}/RMR_p. In the present study, we also calculated each value using raw accelerometry data and RMR_m by the same equations used in the commercially available software (TEE_{ACCm}, $PAEE_{ACCm}$ and PAL_{ACCm}).

RMR

Before the study period, subjects were asked to come to school at 08.00 hours after an overnight fast. After 30 min of rest, RMR_m was measured using an indirect calorimeter with a hood (AR-1; Arco System) at an environmental temperature between 22 and 25°C. This system involved a steady state being established 3 min after the starting of collecting respiratory gas, with the accuracy of RMR measured by this system being 0·02 %[21]. Subjects were placed under a transparent plastic hood that covered their heads and that was connected to the system. After the child had adapted to the hood for 5 min, RMR was measured for 20 min. O_2 consumption and CO_2 production were measured at 1 min intervals and averaged over 6–20 min. Resting status was confirmed by measuring the body temperature and the heart rate.

Table 1. Anthropometric characteristics of the study subjects
(Mean values and standard deviations)

		Age (years)		Height (cm)		Weight (kg)		Body fat (%)		TEE_{DLW} (MJ/d)		RMR_m (MJ/d)		PAL_{DLWm}	
	n	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Grade 1															
Boys	12	12·7	0·7	158·3	10·7	48·1	10·7	22·6	6·1	11·9	2·9	5·9	1·0	1·98	0·26
Girls	7	12·1	0·4	152·9	7·5	40·6	8·4	24·6	6·9	9·1	1·3	4·8	0·5	1·93	0·29
Grade 2															
Boys	10	13·6	0·5	164·1	9·1	51·7	6·0	13·3	9·3	13·8	2·1	6·6	0·9	2·10	0·31
Girls	12	13·5	0·5	155·0	4·5	43·4	3·6	23·5	2·5	9·1	1·4	5·1	0·4	1·78	0·23
Grade 3															
Boys	10	14·6	0·8	163·3	9·4	52·4	4·4	17·0	4·4	11·7	1·9	6·4	0·5	1·83	0·32
Girls	9	14·0	0·0	156·1	5·9	46·1	4·5	24·9	4·6	9·8	2·0	5·2	0·3	1·87	0·32
P															
Grade				0·003		0·098		0·027		0·331		0·037		0·472	
Sex				<0·001		<0·001		<0·001		<0·001		<0·001		0·142	
Grade × sex				0·708		0·900		0·096		0·111		0·777		0·115	

TEE_{DLW}, total energy expenditure measured by the doubly labelled water method; RMR_m, measured RMR; PAL_{DLWm}, physical activity level measured by the doubly labelled water method.

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Table 2. Total and physical activity energy expenditure of junior high school students who did and did not exercise
(Mean values and standard deviations; medians and 25th–75th percentiles)

	Percentage of body fat		TEE_{DLW} (MJ/d)		RMR_m (MJ/d)		$PAEE_{DLWm}$ (MJ/d)		PAL_{DLWm}		TEE_{ACCp} (MJ/d)		Walking steps (steps/d)		Non-wear time (min/d)* Weekday		Non-wear time (min/d)* Weekend	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boys																		
Ex (*n* 27)†	17·3	8·1	12·7	2·4	6·3	0·8	5·2	1·7	2·03	0·30	12·1	2·0	15 920	3730	57	40	77	82
Median			12·9		6·4		5·5		2·03		12·0		16 553					
25th–75th percentile			10·9–14·1		5·8–6·7		3·8–6·7		1·78–2·21		10·8–13·7		13 563–17 970					
Non-Ex (*n* 5)‡	21·6	4·7	11·0	2·4	6·5	1·0	3·4	1·4	1·69	0·20	10·8	1·2	11 170	3182	65	30	70	69
Median			11·1		6·8		3·5		1·71		11·2		10 893					
25th–75th percentile			8·9–13·0		5·6–7·1		2·1–4·7		1·51–1·86		9·2–12·3		8378–14 100					
Total (*n* 32)	18·0	7·7	12·4	2·4	6·3	0·8	4·9	1·8	1·97	0·31	11·9	2·0	15 178	4006	58	38	76	79
Median			12·6		6·5		5·1		1·97		11·9		15 285					
25th–75th percentile			10·7–14·0		5·8–6·8		3·2–6·4		1·73–2·16		10·6–13·4		13 046–17 437					
Girls																		
Ex (*n* 18)†	22·8	2·5	9·7	1·7	5·1	0·4	3·6	1·4	1·90	0·30	9·3	1·1	13 289	2365	72	55	101	78
Median			9·0		5·1		3·1		1·80		9·1		13 325					
25th–75th percentile			8·4–11·4		4·8–5·4		2·7–4·7		1·73–2·06		8·6–9·8		12 047–14 503					
Non-Ex (*n* 10)‡	26·7	6·0	8·7	1·2	5·0	0·4	2·9	1·0	1·75	0·21	9·4	1·6	12 303	2001	69	29	70	40
Median			8·3		4·8		2·5		1·69		9·4		12 568					
25th–75th percentile			7·9–9·3		4·7–5·5		2·0–3·5		1·57–1·91		8·3–10·1		10 869–13 381					
Total (*n* 28)	24·2	4·4	9·3	1·6	5·1	0·4	3·3	1·3	1·85	0·27	9·3	1·3	12 937	2256	71	47	90	68
Median			8·8		5·0		3·0		1·79		9·2		12 885					
25th–75th percentile			8·2–10·3		4·8–5·5		2·5–3·8		1·67–1·94		8·6–9·8		11 974–14 131					
P																		
Exercise	0·041		0·041		0·812		0·010		0·006		0·304		0·004		0·807		0·423	
Sex	0·009		<0·001		<0·001		0·030		0·715		<0·001		0·442		0·481		0·613	
Exercise × sex	0·913		0·540		0·503		0·294		0·288		0·184		0·057		0·681		0·604	

TEE_{DLW}, total energy expenditure measured by the doubly labelled water method; RMR_m, measured RMR; $PAEE_{DLWm}$, physical activity energy expenditure ($TEE_{DLW} \times 0{\cdot}9 - RMR_m$); PAL_{DLWm}, physical activity level measured by the doubly labelled water method using RMR_m (TEE_{DLW}/RMR_m); TEE_{ACCp}, total energy expenditure measured by the accelerometer using predicted RMR.
* Non-wear time: duration of the time that subjects did not wear the accelerometer.
† Ex: subjects who exercised except for the physical education class.
‡ Non-Ex: subjects who did not exercise except for the physical education class.