Review of Scientific Instruments | ARTICLE | scitation.org/journal/rsi

Measurement of the growth of children at weekly intervals

Cite as: Rev. Sci. Instrum. 90, 024103 (2019); doi: 10.1063/1.5018268
Submitted: 5 December 2017 • Accepted: 18 January 2019 •
Published Online: 8 February 2019

View Online | Export Citation | CrossMark

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ABSTRACT

A new method for measuring the growth of children is presented, based on the measurement of the lower leg length during foot movement. This is a touch measurement, but the obtained characteristic of the measured lower leg length, as a function of the pressure force, is reduced to a non-contact measurement. A setup prototype is built and preliminary research conducted. Based on the results obtained, it is concluded that the method allows the observation of increases in child lower leg length at frequent intervals (e.g., weekly). The developed measurement method has a high accuracy, and the results allow for differentiation between periods of child good health and indisposition.

I. INTRODUCTION

Measurement of the current growth of children, as well as observation of growth over time, is a basic tool used in pediatrics to evaluate development and maturation, and for identification of factors of concern. One example is the monitoring of the process of growth in situations where side effects may slow down patient growth such as those caused by medication. In such situations, it is essential to measure a child's growth over a few weeks or even at weekly intervals. This kind of measurement is useful in terms of response to treatment and the effect of treatment on the child's growth dynamics. Standard measurements by tools such as stadiometers or anthropometers, characterized by a relatively low accuracy of measurement, are obviously insufficient. Furthermore, x-ray imaging methods, which have a high accuracy,[1,2] must be rejected due to the need for frequent repetition of measurements and the potential side effects of radiation on growing children.

In medicine, non-invasive and safe optical methods are known and have been developed to measure the geometry of the patient's body, e.g., moiré pattern and photogrammetric methods based on the analysis of the images of markers placed on the patient's body.[3–5] They can also be used in other areas, mainly related to faulty posture evaluation and progress in patient rehabilitation.[6–8]

However, there is a need for useful methods to monitor the growth over shorter time intervals, optimally on a weekly basis. This is often required by clinical situations related to diagnostics or treatment. It is of crucial importance for precipitating the diagnosis and potential modification of treatment. It will enable the assessment of the effects of medicines with known potential stimulation or inhibition of growth, such as growth hormones or glucocorticoids, respectively. In particular, in pediatrics, where patients are in a phase of intensive growth and where therapeutic interventions could violate this process, medicine intended for therapy is subject to exceptionally detailed analysis; the main criteria are effectiveness and safety.

Medicines that are widely used in many specialties and for large groups of patients, which potentially inhibit growth and function directly proportional to the applied dose, require frequent and thorough monitoring of potential adverse reactions. Some studies have focused on one method: the knemometry technique. This method is based on measurements of the lower leg length, i.e., the distance between the knee and heel of a sitting child.[9,10] It generally covers the measurement of two elements: bones and soft tissues. The measurements include those of the tibia, talus, heel bone, ankle joint, knee joint, and soft tissues of the heel and knee.

Measuring devices intended to measure the lower leg are called knemometers. As lower leg lengths differ in children at different ages, different types of knemometers have been constructed: mini-knemometers for infants and small children, and knemometers for older children.[9]

When the measurement of the lower leg is made using a knemometer, there is usually no individual metrological analysis of the uncertainty measurement. The average value of the growth velocity in healthy infants measured by mini-knemometers was 0.45 mm/day,[12] and for children aged 1-3 years, it was 0.1 mm/day with a standard deviation of 0.083 mm/day.[13] In older children, the value was approximately 0.4 mm/week,[14] with a standard deviation of 0.3 mm/week. Error values are often assumed on the basis of the literature, even for entirely new knemometric measurements, as there are no individual metrological analyses. Based on the analysis of the literature cited in this paper, the authors adopt a technical error of approximately 0.2 mm.

Results indicate that the influence and experience of the instrument operator are crucial in obtaining repeatable results,[15] and hence measurements of the same child should be made by the same operator.

A comprehensive analysis of the accuracy of the knemometry method has been presented by Hermanussen,[16] who established certain principles for standardization of a technique of the lower leg length measurement. It was concluded that six repetitions of the lower leg measurement are optimal. However, since the accuracy of the first measurement is less than that of the following measurements, the first one should be eliminated from the analysis. In addition, other rules were established. For example, all measurements should be performed during the afternoon, before examination, the child should stand or walk slowly for 5–10 min (sitting is not recommended and neither is physical activity for at least 2 h before the measurement), and all measurements should be performed by only one person. While maintaining such critical principles, Hermanussen established a technical error for knemometry of 0.16 mm. It was assumed that the technical error is the standard deviation of six independent and successive estimations of the lower leg length. The most published research results have errors below 0.6 mm. However, up to 2% of series have errors above 1 mm.

In the medical literature, the results of knemometric measurements are regarded as a valuable source of information supporting treatment. The method is considered to be more sensitive than laboratory tests,[17,18] and above all, it is non-invasive. Knemometers and the results of studies achieved with their use were realized in pediatric facilities monitoring the process of child growth violated by adverse reactions of pharmaceuticals containing steroids applied in asthma treatment.[11] Studies were also conducted at neonatal units, to assess the development of premature babies in different states of health and with different ways of feeding. Another aim of studies including the use of knemometers was the analysis of the influence of psycho-physical factors on the growth process.

The history of knemometry has shown that precise lower leg length measurements are clinically feasible, but of little practical value because serial measurements of children are inconvenient both for children (and mothers) and for technicians/doctors. Thus, up to now, almost all studies using knemometry have been limited to scientific purposes. There are also many doubts about the accuracy of existing devices.

Although the measurement of the growth of a limb, or more specifically part of a limb, is sufficient to obtain the overall information required to evaluate the correctness of the growth process of children, these types of methods have not become popular in clinical practice. The reason is that the measurements require arduous setup preparation. They are time-consuming, and it is difficult with young patients due to the need to stay still during examination. The accuracy of the results depends on a number of factors. Deformations of soft tissue under pressure and the experience of the operator are of particular importance.

This article presents a new method for measuring the growth of children during short time intervals (e.g., weekly), on the basis of the lower leg length measurement. The new method enables quick measurements without the need to immobilize the child. It uses contact measurements; however, the results are related to conditions of non-contact measurements, i.e., with compensation for the potential pliability of the soft tissue of a child's limb.

II. CONCEPT

The concept for the new method for measuring the growth of children is presented in Fig. 1. The novelty is the measurement of a lower leg length conducted dynamically—during limb movement, which is realized by the dorsiflexion of the foot [Figs. 1(a) and 1(b)]. The new method is based on a contact measurement of the child's lower leg length in a sitting position, but the obtained characteristic of the measured lower leg length, as a function of the pressure force, is reduced to a non-contact measurement. During examination, the distance from the plane touching the surface of a knee to the surface where the child's heel is placed is measured. The movement of the foot causes a change of pressure force F acting on the limb, and the change in the currently measured lower leg length L resulting from pliability of the soft tissue and displacements taking place in the area of the ankle and knee joints.

The current result of the measurement of the lower leg length L is recorded, together with the measured pressure force F evolving over a fixed range from F_d to F_u. The results, correlated measurements of the length and force, are then the points of the function $L = f(F)$, as illustrated in Fig. 1(f).

The influence of the pressure on soft tissue causes deformations that are difficult to assess and are dependent on the child and its physical conditions (hydration, layer of fat, etc.). In the new method, the obtained results of the examination are reduced to the conditions of non-contact measurements,

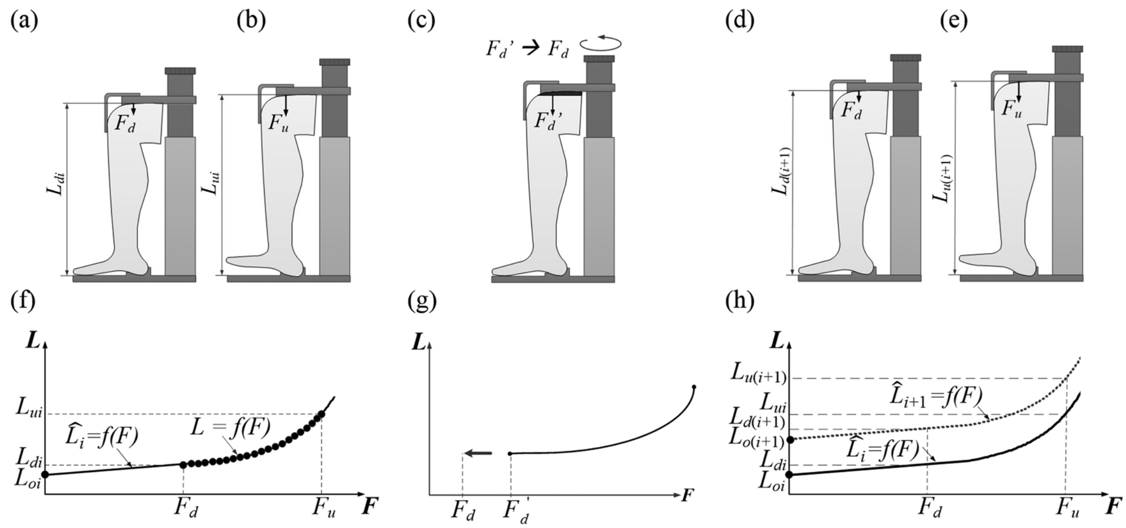

FIG. 1. Growth measurement (a) measurement in the *i*th week of examination, (b) range of the foot movement in the *i*th week, (c) preparation for measurement in the (*i* + 1)th week, (d) measurement in the (*i* + 1)th week, (e) range of the foot movement in the (*i* + 1)th week, (f) characteristics of the length versus pressure force and the fitted theoretical model, (g) adjusting the initial value of the pressure force before entering the next week of examination, and (h) characteristics obtained in the *i*th and (*i* + 1)th weeks.

i.e., when the limb is not affected by the pressure force ($F = 0$). Such a solution allows for eliminating deformations in the soft tissue that occur during examination.

For this purpose, the results of examination obtained in the ith week are analyzed. The first step of the analysis involves estimating the obtained characteristic $L = f(F)$ using the $\hat{L}_i = f(F)$ model [Fig. 1(f)]. Next, using the obtained model, the value of the lower leg length L_{oi} is calculated. This value is obtained by determining the numerical value of the model $\hat{L}_i = f(F)$ for the conditions of non-contact measurements, i.e., for $F = 0$.

The general form of the model used for determining the lower leg length L_{oi} in the ith week of examination can then be presented

$$\hat{L}_i(F) = L_{oi} + \frac{F}{k_s(F)} + \frac{F}{k_m(F)}, \tag{1}$$

where $k_s(F)$ is the elasticity coefficient of the elastic element used in the measuring setup and $k_m(F)$ is the elasticity coefficient describing the soft tissue.

The value of the lower leg length L_{oi} can be approximately expressed by displacement of the model of the equation $\hat{L}_i = f(F)$ in the lower leg axis L.

To determine the change in the lower leg length ΔL_o, examination is repeated after one week ($i + 1$), to determine the weekly growth [Figs. 1(d) and 1(e)], or at another time, according to the adopted time interval.

In the next week of the experiment, before examination, the initial value of the pressure force is corrected, as presented in Fig. 1(c). This is to reduce the value of the pressure force F_d' to the value of F_d, which was the initial value for the measurements made at the previous time. The change in the initial value of the pressure force to F_d is, in fact, a procedure aimed at displacing the set characteristics toward the F axis [Fig. 1(g)]. Such action allows for performing characteristic $L = f(F)$ in the same range of changing pressure force, i.e., in the range F_d to F_u [Fig. 1(h)].

The obtained characteristic $L = f(F)$ in the ith and ($i + 1$) th weeks of measurements, as well as corresponding models $\hat{L}_i = f(F)$ and $\hat{L}_{i+1} = f(F)$, enable specification of the lower leg growth between the examination dates. After determining the lower leg length L_{oi}, on the basis of the results obtained in the ith week of measurements, and $L_{o(i+1)}$ in a similar way in the ($i + 1$)th week [Fig. 1(h)], the weekly value of the lower leg growth ΔL_o can be determined using the following equation:

$$\Delta L_o = L_{o(i+1)} - L_{oi}. \tag{2}$$

III. MEASUREMENT

To perform experimental verification of the method and to determine the $L = f(F)$ characteristic, a prototype of the setup was developed, as presented in Fig. 2(a). The main elements of the setup are two telescopically connected sleeves (1) and (2). A moving sleeve (2) is attached to a profiled plate (3) adjusted to the knee's surface. A profiled polymer insert (4) placed under the child's foot is fixed to the sleeve (1). The child's bent right limb is put between the profiled elements of the setup (3) and (4). Using regulation (5), the initial value of the pressure force F is set by the initial spring tension (8). The test consists of the child raising the foot (dorsiflexion) without losing contact between the heel and the profiled insert (4). Moving the foot lifts the sleeve (2) connected to the sliding encoder read head of the absolute linear shaft

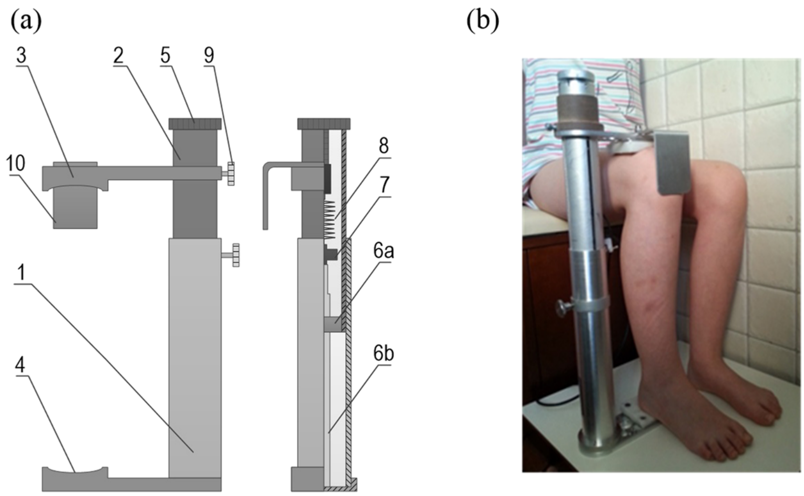

FIG. 2. Setup for contact measurements of a lower leg: (a) schematic diagram and (b) practical implementation.

encoder (6a), which, by moving along the solid steel shaft (6b), allows for recording a temporary value of the lower leg length L. Dorsiflexion of the foot causes the simultaneous spring tension (8) connected to the force sensor (7), whose indication is recorded as the current measurement of the pressure force F. Practical implementation of the setup is presented in Fig. 2(b).

Figure 3(a) illustrates a measuring circuit that transmits and processes the signals, and Fig. 3(b) presents the actual view. The electrical signal from a strain gauge is transmitted via an amplifier (2) into the analog input of a measuring module (4). The Synchronous Serial Interface (SSI) digital signal leaving the absolute linear shaft encoder via the SSI/A converter (3) is sent to the second analog input of the measuring module (4). The power supply of the measuring circuit elements is realized by power supply units (1) of the amplifier, converter, and measuring module.

The measuring module in the system acts as a voltmeter, enabling the simultaneous measurement of voltage signals corresponding to the values of the currently measured length L and pressure force F. The measuring module is connected to a computer, which, using dedicated software, allows for the visualization and presentation of the measured input signals in units of measured values. The software also allows for recording data subject to further analysis.

IV. EXPERIMENTAL RESULTS

The described measuring setup was used to carry out an experiment where one child was examined—a properly developing girl (7 years old). Similar to knemometric measurements, the examination was conducted at the same time of day, at weekly intervals.

Before starting the examination, the child was seated with the right leg bent at the knee at an angle of 90° and put between profiled inserts of the setup (3) and (4) [Fig. 2(a)].

The position of the thigh against the lower leg was further determined by a tile (10) touching the front surface of the knee.

The first examination was preceded by adjusting the structural elements of the setup to the child's height, which were then fixed (9) [Fig. 2(a)], and remained unmodified during the entire experiment.

Over one day, five measurement series (j = 5) were performed. One series was interpreted as the single placing of the child on the setup and moving the foot. The dorsiflexion of the foot in one measuring series was repeated several times, in the range of movement within the physical abilities of the child. After each measuring series, the child was taken off the setup and asked to take a few steps. When performing a measuring series, the range of foot movement was controlled by monitoring the force range from F_d to F_u, as presented in Fig. 1, in such a way that the measurement was made within the same range of changes.

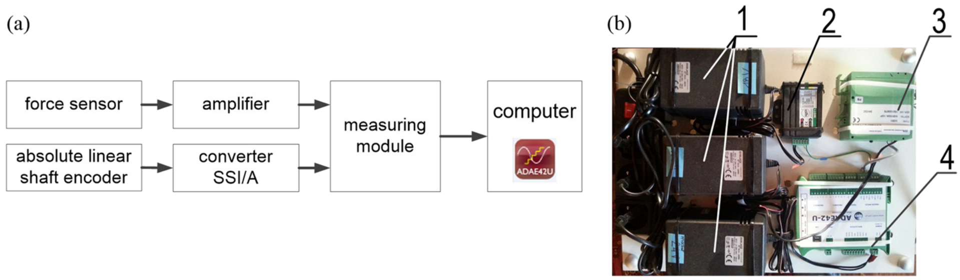

FIG. 3. Measuring circuit: (a) flow diagram and (b) practical implementation.

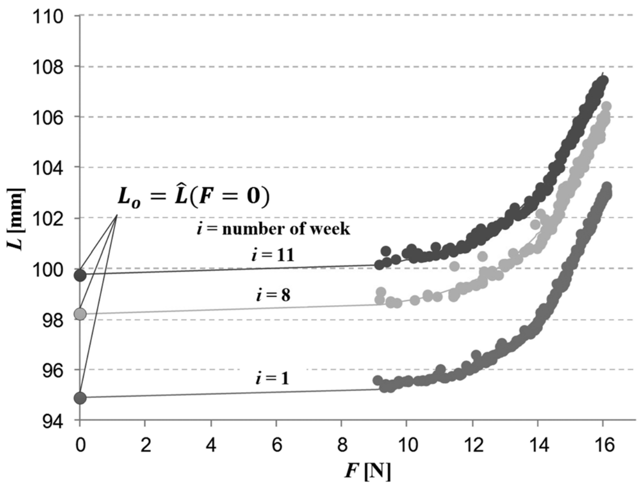

FIG. 4. Exemplary models and results of measurements.

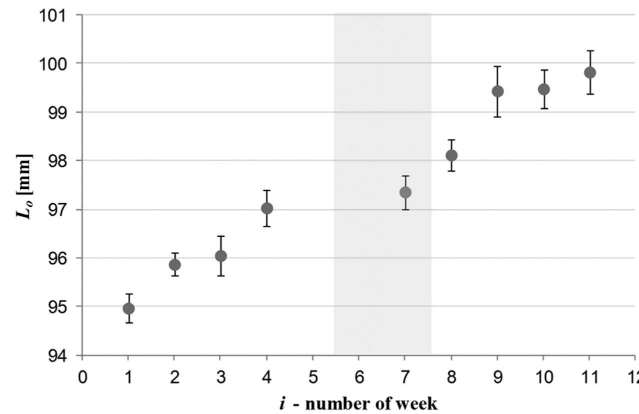

FIG. 5. Measurements of lower leg length L_o, including interval, during which the child was ill.

Figure 4 shows exemplary results of measurements obtained in selected weeks of measurement (i = 1, 8, 11) and models describing them. The obtained characteristics acknowledge the value of the force of gravity originating from the moving part of the setup being lowered onto the surface of the knee during examination. As a result of such correction, the presented models describe the measured lower leg length L as a function of force F actually affecting the limb during examination. On the basis of the results obtained, the examinations performed in later periods cause displacement of the characteristics toward the y axis, corresponding to the measured lower leg length L.

The shape of the characteristic is obtained as a result of the properties of the spring element introduced into the setup, as well as the deformations in the soft tissue of the limb, according to Eq. (1). The spring used in the setup was selected in such a way that its properties specify the shape of the determined characteristic. For measurements made with the spring element applied in this particular case, the results obtained in the examination can best be described by

$$\hat{L}(F) = L_{pij} + L_{fi}e^{c\cdot F}, \tag{3}$$

where L_{pij} is the unadjusted length of the lower leg L_{oi} obtained in the ith week of the measurement, in the jth measuring series, and L_{fi} is a coefficient representing the error for determining the lower leg length resulting from the repeatability of the settings of the initial value of pressure force F_d in the ith week. The parameter c in Eq. (3) is a constant coefficient related to the shape of the characteristic; i.e., it represents the resultant coefficient of elasticity of the system.

For the ith week measurement series, the evaluation of compatibility of the results with the adopted model, described by Eq. (3), was carried out. The performed regression analysis confirms the adequacy of the model used. This is evidenced by the value of the squared correlation coefficient (R^2), which indicates that, on average, 99.2% of the result variability explains the adopted model of regression.

On the basis of the adopted model of Eq. (3), the values of length L_{oi} were calculated, i.e., the values of the model for F = 0. Figure 5 presents the determined values of L_{oi} derived from a few months of measurements of the child.

It can be observed that the increase in L_{oi} values in the following weeks of examination (Fig. 5) corresponds to the displacement of the determined characteristic $L = f(F)$ toward the y axis presented in Fig. 4. The values of L_{oi} at weeks 5 and 6 are missing due to omitting the examination at week 5, and at week 6, the child was sick and vomiting. The results from weeks 7 and 8 differ from the other weeks, and are a consequence of slowing increase in the lower leg length due to sickness and convalescence of the child in that period, as shown in Fig. 5. The measured part of the limb actually covered: the length of the tibia, the joint of the knee, the ankle joint, and soft tissues covering the heel and the knee, as well as the talus, calcaneus, and parts of the foot.[9] The observed results of the examinations from weeks 7 and 8 illustrate the changes in the soft tissue only. Despite its insignificant share in relation to the entire length of the measured limb, it can be observed that child dehydration affects the growth of a lower leg.

Further examination was conducted after the child recovered. The L_{oi} values achieved in this period were similar to those of weeks 1-4 when the child was healthy. Although it is generally assumed that the growth of a lower leg is linear, Fig. 5 shows that this is not the case. As the process of growth is a combination of many factors (genetic,

TABLE I. Values of ΔL_o determined as an example.

Numbers of weeks i	Interval (weeks)	ΔL_o (mm)	$u(\Delta L_o)$ (mm)
1-4	3	2.06	0.53
7-10	3	2.12	0.57
8-11	3	1.70	0.54
3-7	4	1.31	0.59
7-11	4	2.46	0.55

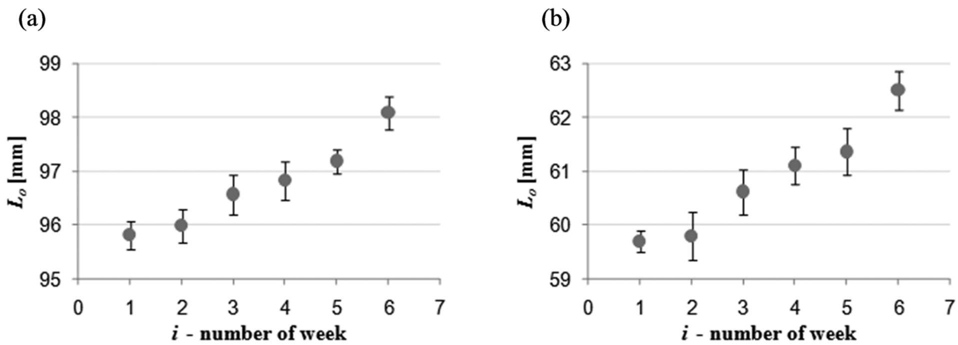

FIG. 6. Measurements of lower leg length L_o of the two children: (a) boy, 12 years old, and (b) girl, 10 years old.

psychosocial, dietary, hormonal, and others), the heterogeneity of the obtained results is a natural phenomenon.

The error bars in Fig. 5 correspond to the values of uncertainty $u(L_{oi})$, which are a combined standard measurement uncertainty. On the basis of Eq. (3), a mathematical model of measurement can be developed and the combined standard measurement uncertainty $u(L_{oi})$ estimated,

$$L_{oi} = \bar{L}_{oi} + p_l + w(p_k + p_m) + p_{fi}. \tag{4}$$

Five measurement series ($j = 5$) were performed on each measurement day, and from the five obtained values of L_{pij} corrected for the determined in the ith week coefficient L_{fi}, the average length of the lower leg was specified, as well as the distance R_{Loi} and resulting standard uncertainty $u(\bar{L}_{oi})$. The error of the setting force F_d, which is connected to the value of L_{fi}, is acknowledged in Eq. (4) by the correction p_{fi} from which a standard uncertainty $u(p_{fi})$ can be obtained. Another source of measurement uncertainty is the absolute linear shaft encoder applied in the setup and the system error related to it. This is expressed in Eq. (4) by a correction p_l described by a standard uncertainty $u(p_l)$. Other sources of uncertainties are the measuring circuit and converter, and the associated measuring module errors. The error of the converter applied in the setup is expressed in Eq. (4) by the correction p_k and the error derived from the measuring module by correction p_m. Standard uncertainties $u(p_k)$ and $u(p_m)$ related to corrections p_k and p_m are estimated on the basis of the technical documentation of the converter and the measuring module. The parameter w in Eq. (4) is associated with the share in the combined standard uncertainty of the measuring circuit. As the measuring signal processed by the measuring circuit is an electrical signal from the linear shaft encoder, the role of the multiplier w is a reference to the unit of length.

Based on a chosen pair of results, the weekly value of the lower leg length ΔL_o can be determined from Eq. (2), and similarly for any adopted time interval. The values of the lower leg length growth ΔL_o determined as an example are shown in Table I.

After selecting the first examination term and establishing the time interval, the corresponding increase in the lower leg length ΔL_o was determined, as shown in Table I. It can be observed that apart from the adopted time range, the value of the growth also depends on the period of analysis. On the basis of the results presented in Fig. 5 and the results included in Table I, it can be observed that the increase in the lower leg length ΔL_o for the same interval may differ because the pace of the growth process is affected by a number of factors. For the examined child at a 3-week interval, the determined growth of the lower leg length ΔL_o was in the range 1.70–2.12 mm. For a 4-week interval, during which the child was ill, the growth was almost half the value when the child was healthy.

The initial estimated combined standard uncertainty $u(\Delta L_o)$ of the calculated growth of the lower leg ΔL_o is approximately equal to 0.5 mm. The differences in the values of measurement uncertainty $u(\Delta L_o)$ are mainly caused by the range of results obtained in one term of examination. The standard uncertainty from the measuring instrumentation is 0.08 mm. This parameter is comparable with the technical error in the literature.[9,16]

On the basis of the results, the average value of the weekly growth of a lower leg $\Delta\bar{L}_o$ was determined, calculated from all pairs of results obtained during the entire cycle of examination. The value is 0.53 mm with a standard deviation of 0.23 mm.

To demonstrate the applicability of the proposed method more studies were performed. Figure 6 presents the values of lower leg length L_o of the two children: boy, 12 years old [Fig. 6(a)] and girl, 10 years old [Fig. 6(b)], derived from a six weeks of measurements. The results presented in Fig. 6 are substantially different from the single case currently reported previously in Fig. 5 because they do not include intervals during which the children were ill.

In both cases, it can be observed the increase in L_o values in the following weeks of examination, what seems to be normal when the children are healthy. The average values of the weekly growth of a lower leg of examined boy and girl are equal to 0.47 mm and 0.54 mm, respectively.

The presented results are very promising and ensure the effectiveness of the proposed method. The proposed method has been validated making precise measurement of the growth of children clinically feasible. Further research will be conducted with the large group of studied cases to be published in a future paper.

V. CONCLUSIONS

The method described here is a new solution applicable in short-term growth evaluation of children. Similar to previous methods, this method is based on the measurement of the lower leg length. However, the measurement is not made at one position of a limb at one point only, but when the limb is moving, and the characteristic of the currently measured lower leg length L is found as a function of the pressure force affecting it.

In the described method, the impact of pliability of the soft tissue was eliminated by bringing the contact measurements of lower leg L_0 to non-contact measurement conditions. Apart from relating the obtained length of the lower leg L to the conditions where $F = 0$, the characteristic $L = f(F)$ determined in the examination additionally allows for averaging the unique response from the soft tissue area submitted to the pressure force. Moreover, the way of determining the lower leg length L_0 on the basis of the characteristic is not susceptible to other random factors that may occur during the measurement. The measurement time is mainly connected to the number of realized measurement series and the number of foot movements made in each of them. Although the conducted experiment covered five measurement series, the time for performing the examination was several minutes in total. Performing the examination does not require the child to remain still, which makes it significantly more convenient than measurements conducted with knemometers. In this case, the examination requires the child to be active so that they feel engaged in the measurement process and thus willingly participate in the examination.

Based on the observations and experiences, it is concluded that the developed instrument is suitable for measuring the growth of children in the age range 3–12 years. However, it is difficult to define the lower limit of the measuring range unambiguously because it depends more on the personal characteristics of the measured child than the technical and constructional capabilities of the instrument. The condition for measurement is the child's cooperation with the operator, which also depends primarily on the child's intellectual maturity and temperament.

On the basis of the obtained results, it can be concluded that the new method allows for observing even weekly increases in the lower leg length. From the growth results obtained, it is possible to differentiate between periods when a child is healthy and when they are ill.

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