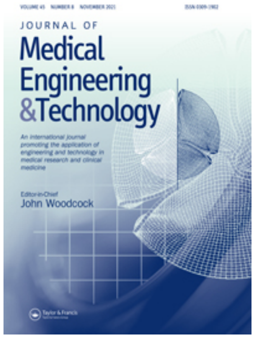

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REVIEW

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Review of recent innovations in portable child growth measurement devices for use in low- and middle-income countries

Geoffrey Neale[a,b]*, Santosh Gaihre[b]*, Pearse O'Gorman[a], Ruth K. Price[b], Ane Galdos Balzategi[b,c], Catalina Herrera Barrientos[b,d], Shweta Rawal[e], Margaret Morgan[a] and Helene McNulty[b]

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ABSTRACT
Improving nutritional status is fundamental to addressing challenges in child health in low- and middle-income countries (LMICs) and a priority for international organisations such as the United Nations Children's Fund (UNICEF) and the World Health Organisation (WHO). Despite the global consensus that child growth is a key indicator of child nutrition and health, the development of low-cost, accurate and child-friendly growth measurement devices that are fit for purpose in LMICs remains elusive. Recognising these limitations, UNICEF recently published a Target Product Profile (TPP) calling for the development of new state-of-the-art height and length measurement devices. The purpose of this review was to examine current growth measurement devices in relation to this UNICEF TPP requirement and set the stage for the development of new devices. The findings show that there is a gap in the product market for accurate portable length and height measurement devices. In particular, our review indicates that devices in current use generally lack capabilities for automated data recording and transfer of data to a central database, and are often not child-friendly. We conclude that future innovations in length and height measurement devices should focus on addressing these issues.

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Height/length measurement devices; child health; anthropometry; design performance; low- and middle-income countries

1. Introduction

Despite numerous interventions, childhood malnutrition stubbornly persists as a global health concern and is responsible for an estimated 45% of deaths in children below the age of 5 years across low- and middle-income countries (LMICs) [1]. As a result, the United Nations Children's Fund (UNICEF), whose primary focus is the health and wellbeing of children globally, places particular attention on children in LMICs, where inadequacies in local health care systems require international support and interventions. Measurement of Early Childhood Development (ECD) involves collecting anthropometric data relating to child length (recumbent length in children below 24 months who cannot stand), height (standing height in children above 24 months), weight and head circumference, and is vital to accurately assessing nutrition, growth and development in children and adolescents [2,3]. ECD monitoring in high-income countries has been proven to facilitate early identification of children at risk of developmental delay, thus enabling appropriate interventions at societal, family and individual levels and reducing health inequities [4]. When referenced against World Health Organisation (WHO) Growth Reference Charts, child growth measurement data can detect undernourishment in the form of stunting (low height for age) and/or wasting (low weight for height) in children and serves as an indicator of malnutrition and underlying medical conditions [5]. In LMICs in particular, where one in four children under the age of 5 years suffer at least one dimension of child growth failure [6], child growth measurements can be applied to identify and treat children at greatest risk of malnutrition and help to lower child mortality [2,7].

In high- and upper-middle-income countries, local healthcare systems in hospitals, clinics and doctors'

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offices are typically equipped with modern and accurate instrumentation for child length/height measurement, usually in the form of infantometers (length) and stadiometers (height). In LMICs, however, these conditions often do not hold true. In the worst of conditions, children do not have access to local health care facilities and are reliant instead on visits by representatives of UNICEF or the WHO for basic health services. Conducting child length/height measurements in the field can be particularly problematic compared to other anthropometric measurements, and the collection of high-quality data challenging, especially in rural communities in LMICs.

1.1 Statement of the problem, aims, objectives

Potential inconsistencies in anthropometric measurements are well recognised and as a result WHO has developed a set of standards and procedures [8] to minimise errors and improve the reliability of these measurements [9,10]. Apart from less than ideal conditions in which the data are typically collected, the equipment used is often dated, heavy, inaccurate and imprecise. The accuracy of length and height measurements is a particular concern as the tools typically used in LMICs – basic wooden boards and tapes – are the most susceptible to measurement error [9,11]. Moreover, the equipment in current use requires manual data reading and recording, thus the process is subject to human error at multiple steps. UNICEF has recently raised concerns in relation to the accuracy of techniques for measuring child length and height [12], in turn calling into question the validity of the data being obtained and reported [9]. UNICEF has described the main factors that cause errors in length/height data collection as the following [12]:

- Inaccurate positioning of the body against the measuring device;
- Child movement during measuring procedure;
- Reading off the measurement from the wrong angle (parallax error);
- Difficulty reading measurements in poor conditions, e.g., due to poor lighting which leads to rounding up/down of values;
- Manual data entry error.

Errors from these medical assessments can hinder the detection of growth defects, particularly in LMICs where the accurate recording of growth is critical for evaluating a child's health status because it is often not supplemented by any other ECD monitoring [2]. Furthermore, inaccurate data can undermine the analysis of the health impacts of UNICEF interventions in LMICs [13]. Although 45% of governments have national ECD policies and programmes involving child growth monitoring [2,14], the challenges in measuring, recording and interpreting growth data can greatly limit the ability to generate reliable evidence to support effective interventions [10,14]. Improved tools for data collection that provide reliable results and that are not prone to operator error are urgently needed. Recognising these limitations, UNICEF published a Target Product Profile (TPP) in 2017 calling for the development of new state-of-the-art height and length measurement devices [12]. Therefore, the aim of this review was to evaluate portable devices currently available for measuring length and height against UNICEF's TPP and to identify gaps in the market where the development of new devices is needed.

2. Standard practice for collecting child length and height data

The procedure for obtaining length or height measurements is guided by WHO regulations [8] and requires the use of a measuring board with a movable footboard (for length measurement) or headboard (for height measurement). To measure the recumbent length in infants under the age of 24 months or in children who cannot stand, the child must be laid horizontally on the measuring board with eyes looking vertically upwards, perpendicular to the board (Figure 1(a)). The mother or caregiver is needed to help hold the child's head in this position and make sure the crown of the child's head is in contact with the fixed headboard. The legs of the child are then straightened gently by an operator and the footboard is moved to touch the soles of the child's feet, with toes pointing directly upwards. The measurement is observed by the operator. For small children, guidance on the necessary adaptations indicates that two people are required: one to move the footboard and record the result, and the other to ensure that the correct positioning of the child is maintained. For standing height, the child must then stand on a flat surface, with weight evenly spread, heels together and head parallel to the floor so that the eyes are looking straight ahead maintaining the "Frankfort Plane" (an imaginary line from the centre of the ear hole to the lower border of the eye socket) (Figure 1(b)). Arms should hang freely with the head, back, buttocks and heels all in direct contact with the vertical board. The headboard is then lowered so it comes into contact with the

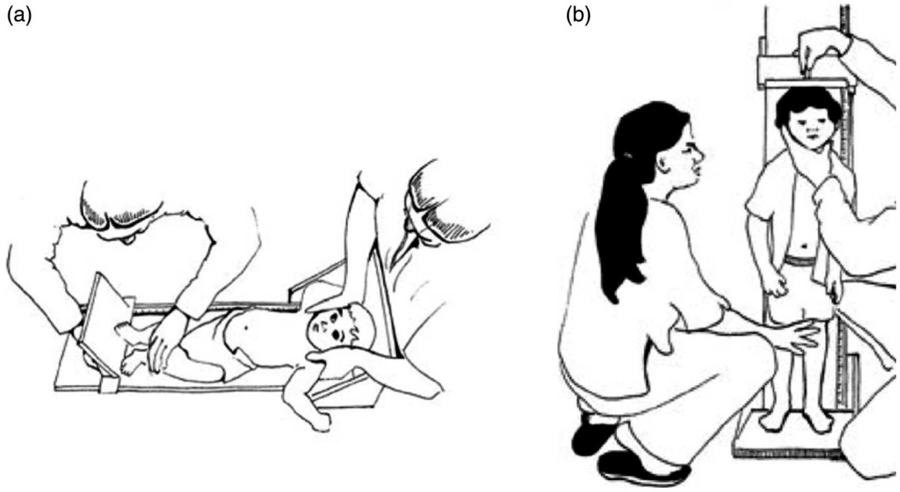

Figure 1. Images showing the (a) the portable baby/child length and height measuring board [15] and (b) portable baby/child/adult length and height measuring board [16] currently in use by UNICEF.

crown of the head. At this point, the child should inhale fully to maintain a totally vertical position until the measurement is observed by the operator. In both cases, the result is then recorded to the nearest millimetre.

There are currently three devices in use by UNICEF for the measurement of child length/height [12]:

- A portable baby/child length and height measuring board, made of wood with a range 0–120 cm and an accuracy/precision of ± 0.2 cm. This device is designed to measure the length of children below 24 months in the recumbent position [15].
- A portable child/adult length and height measuring board, made of wood with a range of 0–210 cm and an accuracy/precision of ± 0.2 cm (2 items: mainboard and an extension). This device is designed to measure the height of children above 24 months in the standing position [16].
- A portable child length/height stadiometer, made of plastic with an accuracy/precision of ± 0.2 cm. (2 devices: one for length measurements and one for height) [17].

In all three cases, the child is placed into the measuring space in the device and held or assisted by an operator and/or their parent. These devices are simple and effective but are typically cumbersome, requiring multiple operators. Although a large selection of portable devices for measuring child growth are commercially available and are discussed in this review, two main problems that are explicitly stated by UNICEF remain largely unaddressed.

First, measurements are often read and recorded manually and although this makes the process simple (requiring minimal training), it introduces human error. Operators can read off values incorrectly, round values up or down for ease and/or record values incorrectly. A desirable capability would be, not only a digital display feature but a device that automatically records values and transfers that data to a central database thus removing the need for manual data recording. It should be noted however that digital data storage can introduce complications associated with data security and this should be considered in any product/system design.

The second problem is that devices are often not child-friendly. This is a particular problem for children below 24 months where operators face challenges with correct positioning of the child on the device and child movement during measurement. In addition, the need to lightly press children's knees to straighten their legs causes distress to the child, parent and operator; approaches that do not require this step are highly desirable.

3. State-of-the-art in child growth measurement devices

For the purposes of this review, and in line with UNICEF guidelines, child growth measurement devices are considered in two broad categories: devices to suit children below the age of 24 months that measure recumbent length; and devices to suit children above the age of 24 months that measure standing height.

3.1. Metrics used for reviewing and comparing child growth measurement devices

In order to provide constructive and relevant commentary about the range of devices that meet the

Table 1. Key operational/functional requirements for height/length measurement devices as defined in the UNICEF TPP [12].

Operational requirement	Minimum performance	Ideal performance
Accuracy	Field measurement of humans (infants, children and adults) recorded by trained surveyors within ±3 mm	Field measurement of humans (infants, children and adults) recorded by trained surveyors within ± 1 mm
Range	30–215cm	
Precision	± 2 mm	±1mm
Temperature	−10 to +45	
Humidity	80% relative humidity	
Mass	Max. 6 kg	Max. 2 kg
Output display	Clear digital readout in dimly light settings with one decimal digit (mm).	Back-lit LCD screen or similar for low light anti-glare screen with high contrast for bright light reading
Data collection	Reading to remain on the display until the device is activated again.	-Outputs are automatically recorded, and data automatically transferred to the preferred device, even with low battery power. (see data storage capacity under operational/ functional requirements). -Connectivity range within 10 m -Preferably meeting IEC 60601-1:2015 or equivalent Standards for medical Electrical
Price	150–200 USD	300USD
Durability	The device must be able to withstand the intended use during its operational life without compromising functionality or accuracy. The durability can preferably be demonstrated by being compliance to EN 62262 IK 09 or equivalent for impact resistance and compliance to IEC standard 60529, IP53 for water particle size permeability	

Table 2. Key physical and public health attributes to consider in the evaluation of available devices.

Physical attributes	Public health attributes
• Transportation – Devices should be portable *via* multiple means of transportation including cars, motorbikes, boats, public transportation and on foot, often in rough terrain. • Environmental – Temperatures can range from extreme heat combined with high humidity and sunlight exposure to freezing, with extreme freezing being uncommon.	• Accuracy – Should allow for the in-the-field measurement of humans accurate to ±3mm. • Training – Field operators usually have a minimum of secondary education but operators with a higher education level are common. The field operator may occasionally have less than secondary level depending on the country and the additional tasks of the operator. • Child friendliness - The device must be child-friendly and designed to avoid distress or harm to the child by incorporating soft edges/ surfaces and child-friendly colours and illustrations which are gender neutral and appealing to all cultures. • Price – The device should cost less than the US $300.

UNICEF TPP, some evaluation metrics must be defined. Table 1 lists in detail, the operational/functional requirements for these devices based on their intended operating environment, as extracted from the UNICEF TPP for Height/Length Measurement Device(s) [12]. Any device/method satisfying the majority of these operational/functional requirements is included in this review. The key physical and public health attributes of relevance for evaluating the available devices are listed in Table 2. In addition, the important international standards outlined in the UNICEF TPP [12] that these devices must meet or be able to meet are presented in Table 3.

Table 3. The key international standards outlined (ISO) in the UNICEF TPP.

1. ISO 13485 Quality Standard for Medical Devices [18] – Design, production, installation and servicing of medical devices and related services.
1. ISO 14001 Environmental Management [19] – This standard helps to protect the environment by preventing adverse environmental impacts, reducing the environmental impact of the organisation and enhancing environmental performance.
1. IEC60601-1 Basic Performance and Safety Requirements [20] – outlines requirements for medical devices to operate safely in medical and non-medical surroundings, whether used by trained or untrained staff.
1. BS EN 62262 IK 09 Impact Resistance [21] – outlines the impact strength of electrical equipment and specifies the capacity to which a component can protect against impact damage. Impact resistance is measured by means of IP codes from IK00 to IK10 with IK09 is representative of 10J of kinetic energy in the form of an impact.
1. IEC 60529, IP53 [22] – refers to dust protection and resistance to sprays of water.

3.2. Children below 24 months

3.2.1. Infantometers and measuring boards

The use of measuring boards or mats is the most common method of measuring recumbent length in children below the age of 24 months in both clinical and non-clinical environments [8]. More refined versions of these devices come in the form of infantometers, which are typically designed for use in a clinical environment, are more accurate and can provide additional functionality such as a weight measurement. Many different recumbent lengths measuring devices are commercially available and range from simple measuring mats to clinical infantometers. A detailed list of these

Table 4. List of child growth measurement devices and specifications used for children below 24 months.

Product name	Dimensions (cm)	Mass (kg)	Temperature range (°c)	Measurement range (cm)/minimum gradations (mm)/ Error (mm) Test-retest reliability	Price (US$)
	Measuring mats				
Seca 210 [23]	L: 134.0 W: 30.0 H: 14.0	0.5	+10 to +40	10 to 99 5 ±5 –	83.00
Marsden HM-110 baby measuring mat [24]	L: 30.0 W: 8.0 H: 10.0	–	–	10 to 110 5 – –	£25.00 (33.00[a])
Charder HM110M [25]	L: 140.0 W: 30.0	0.4	−5 to 35	10 to 110 5 – –	55.00
Hopkins measure mat II [26]	L: 135.0 W: 31.0 H: 14.0	0.5	−10 to +40	10 to 99 1 – –	49.95
	Rod-style infantometers				
Seca 207 [27]	L: 104.0 W:12.0 H: 28.8	0.81	–	7 to 99 1 – –	144.00
Charder HM80M [28]	L: 62.0 W:27.0 H: 7.0	0.7	−5 to 35 (−20 to +60)[b]	35 to 80 1 ±10 –	72.00
Charder HM80P [29]	L: 89.0 W: 33.5	0.688	+5 to +35 (−20 to +60)[b]	10 to 80 1 ±10 –	64.00
Charder HM101M [30]	L: 104.0 W: 27.5 H: 5.5	0.8	+5 to +35	10 to 100 1 ±10 –	–
Marsden HM-80P [31]	L: 88.0 W: 10.0 H: 33.0	–	–	10 to 80 1 – –	£45.00 (59.00[a])
Cardinal Detecto digital length measuring device [32]	L: 62.0 W: 29.0 H: 7.0	0.7	+10 to +40	35 to 80 1 – –	273.00
Charder HM80D [33]	L: 62.0 W: 29.0 H: 7.0	0.7	+5 to +35	35 to 80 1 ±10 –	185.00
	Cradle-style infantometers				
Seca 416 [34]	L: 10.5 W: 16.5 H: 40.2	3.2	–	33 to 100 1 – –	555.00
Seca 417 [35]	L: 11.2 W: 31.0 H: 12.0	1.6	−10 to +40	10 to 100 1 – – ±5	222.00
Hopkins 3 in 1 measuring board [36]	L: 200.0	5.7		0 to 200 1 – –	576.75
	Photographic measurement				
Fletcher et al. [37]	–	–	–	– – ±15–± 36 depending on lighting –	–
Tang et al. [38]	–	–	–	– – ±11 –	–

[a]Indicates price from manual conversion based on the exchange rate in July 2020.
[b]Indicates allowable storage temperature range if given.

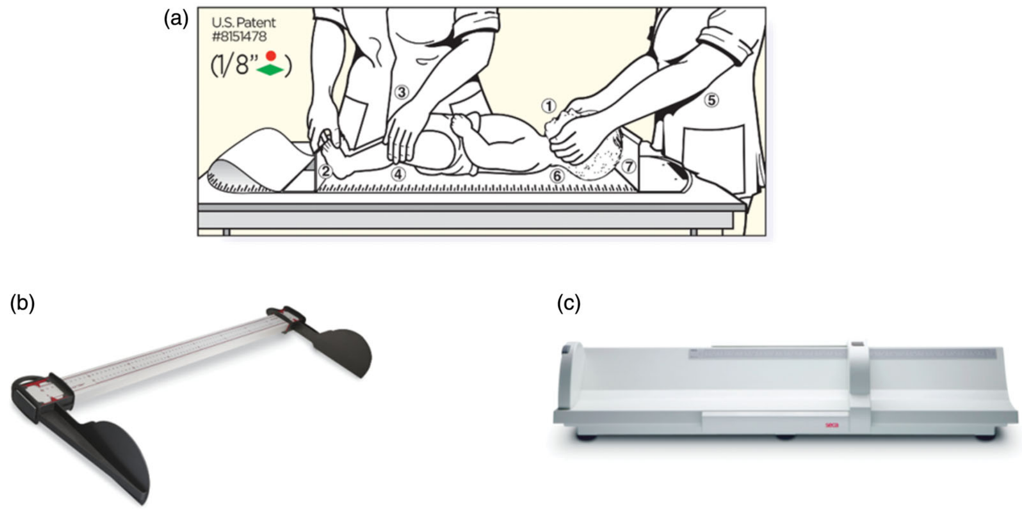

Figure 2. Image showing (a) the operation of an infant measuring mat [26], (b) the Marsden HM80P portable infantometer [29] and (c) the Seca 416 infantometer [34].

devices is given in Table 4, along with their technical specifications related to the requirements provided in the UNICEF TPP document [12].

A typical baby measuring mat is shown in Figure 2(a). Designs show little variation between manufacturers and are developed for use in paediatric hospitals, clinics and home visits by midwives. These mats are typically light (weighing around 0.5 kg), and can be rolled up, stowed and easily transported. They do not have any defined environmental conditions that would hinder their operation and generally meet the required temperature range (–10 °C to +45 °C) defined in the UNICEF TPP. The operation of these devices is straightforward and does not vary significantly from the operating procedure described in the training manual and course currently provided by UNICEF and WHO [8]. They are also the cheapest devices, typically costing between the US $30 and $83 per unit.

Measuring mats suffer from two main drawbacks. Firstly, because the material is flexible, the mat must be placed on a perfectly flat surface to allow for accurate measurement. On uneven surfaces, the measuring region becomes distorted, which diminishes accuracy. An uneven surface would also be uncomfortable for the infant being measured and resulting in distress for the child and the family member. Secondly, the manual reading off and recording of recumbent length data does not satisfy the highlighted need for digital, and preferably automated data recording as set out in the UNICEF TPP. This device, like the existing measuring UNICEF boards [15,16], requires two operators and can be distressing for both the child and the family member because the child must be restrained and its legs straightened to provide an accurate measurement.

Alternatively, recumbent length can be collected using infantometers, which are either rod-style or fully integrated cradle-style devices. Rod-style infantometers with movable paddles (Figure 2(b)) can typically be integrated into other systems offered by a given manufacturer to provide data for both height and weight in one integrated device. These devices, like the measuring mats, are light and easily transportable, weighing between 0.7 kg and 0.8 kg. They also do not have any defined environmental conditions that would hinder their operation. They typically have an operating temperature range of between −5 °C and +35 °C which doesn't fully satisfy the UN TPP temperature range of −10 °C to +45 °C. These devices cost between the US $59 and the US $144 per unit, which is in the same price range as the measuring mats. Operation is straightforward and should require training no more intensive than what is already offered by UNICEF [8].

Digital versions of rod-style infantometers are also available [32,33]. These have all the advantages of rod-style infantometers with the noted benefit of a digital display for length measurement (which removes the possibility of the operator "rounding" up or down of the measurement). Digital infantometers typically cost between US $185 and the US $273 per unit, falling within the US $300 price range. These devices have reduced operating temperature range of +5 °C to +35 °C compared to the previously mentioned analogue versions of these devices. This is because the temperature has very marked effects on the discharge and storage life of batteries and the general operation of electronics. The use of these digital devices would likely require additional training

(a) (b)

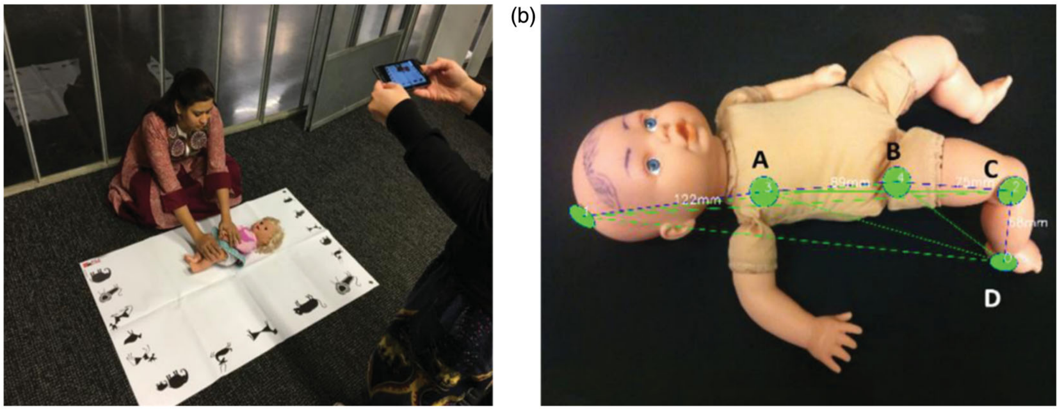

Figure 3. Images showing (a) baby doll being held on a specially designed blanket during the testing of the Baby Napp software in Fletcher et al. [37] and (b) baby doll showing the placement of feature marker stickers in Tang et al. [38].

for operation, data storage (if possible) and calibration.

Rod-style infantometers do not include their own cradle or measuring surface. The major challenge as it relates to their use in LMICs is the need for a perfectly flat, comfortable and clean surface on which to place the infant during the measurement, which is not always available. In contrast to the minimalism of the rod-style design, fully integrated cradle-style infantometers with a rigid measuring area (Figure 2(c)) are also available on the market [34–36]. Although they include their own infant support surface, these devices still require a relatively flat surface on which to place the device. Since the infant does not come into contact with the surface, less desirable surfaces, like the floor or ground can also be used. Most of these devices fall at the top end of the price range but costs can exceed the target price, costing between the US $222 and the US $576 per unit.

With the exception of digital devices, there is no real difference in the accuracy of most of these measuring mats and infantometers. None of the devices discussed to meet the ±3mm minimum accuracy threshold set out in the UNICEF TPP, instead, they exhibit recorded errors between ±5mm and ±10mm. Most have minimum gradations of 1 mm, with the noticeable exception of the measuring mats (i.e., the Seca 210, the Marsden HM-110, the Charder HM110M and the Hopkins Measure Mat II) which have minimum gradations of 5 mm. The common issue amongst all these devices are that they do not address the two highlighted gaps in the product market regarding automatic data recording and child-friendliness. Although digital infantometers provide a digital readout to store measurements, manual recording into a database by a human is required. All of these devices require manual straightening of the child's legs to provide accurate measurement which was identified by UNICEF as one of the major issues with the existing measuring equipment [12]. In summary, no recent innovation or advancements of infantometer type measuring equipment have been reported and all devices follow the same principle using an adjustable measuring gauge.

3.2.2. Photographic measurement techniques

More recently, with the rapid development of portable camera technology (specifically cameras integrated into smartphones), image-based approaches for measuring infant length are being developed. Fletcher et al. [37] developed a low-cost, smartphone-based health screening platform that allows community health workers to collect data from a child without any manual data recording. Baby Napp software was designed for Android mobile devices and is capable of measuring length, weight and middle-upper arm circumference. To measure infant length, the subject is placed on a specially marked blanket/mat and a photo was taken from which the child's length is automatically extracted by the Baby Napp software. The blanket (Figure 3(a)) has a series of optical patterns in the form of animal drawings, acting as an augmented reality target used by the image tracking software for calibration.

The Fletcher et al. [37] system has a number of attributes. It is easily transportable, consisting of a smartphone and a flexible mat that can be easily folded away. Most smartphones can operate within the defined UNICEF TPP temperature range (-10 °C to +45 °C) and, with more smartphones becoming water-resistant or even waterproof, humidity and splash resistance are also ensured in alignment with IEC 60529, IP53. Data is automatically stored by the software and can be uploaded to a central database *via*

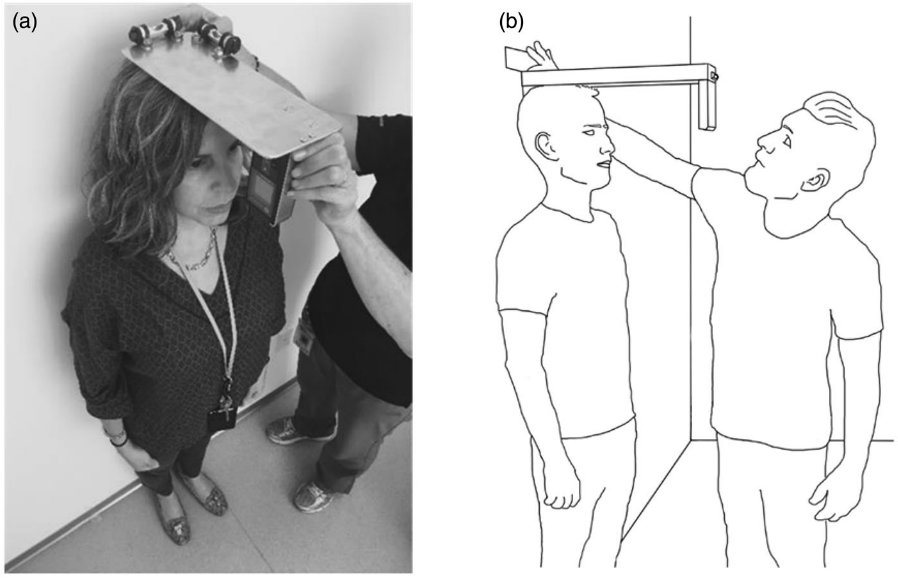

Figure 4. Images showing (a) operation of the prototype in Mayol-Kreiser et al. [46] and (b) the operation of the prototype used in Sørensen et al. [50].

the internet (when and where available) or *via* physical data transfer. This removes manual data recording errors, and together with the child-friendliness of the device, fills the two major highlighted gaps. The cost of this system cannot be fully assessed because the software and accompanying paraphernalia (e.g., the blanket) are not commercially available. Given that a smartphone is required, however, the cost of which can vary significantly and, in some cases, cross the US $300 maximum, this may be a limitation. Also, although the software has been validated in a laboratory setting against traditional manual measurement techniques, it has an error of ±12mm which is larger than the error range of measuring mats and infantometers (between ±5mm and ±10mm).

Tang et al. [38] also developed an image-based approach for measuring infant height/length using a smartphone. In contrast to Fletcher et al. [37], the Tang et al. system uses physical feature markers in the form of stickers that must be manually attached to the infant at the joints along its length (Figure 3(b)). There are however a number of challenges associated with this approach. As it is difficult to take a single clear picture containing all the stickers, the authors took the approach of using separate pictures dividing the body up into manageable sections. Operators must be trained to properly place and attach markers and how to take pictures to get the most accurate results, raising concerns about considerable training needs required by this method and the potential for inter-operator variation. Tang et al. [38] do not comment on costs, but it can be assumed that these would be similar to Fletcher et al. [37] system, including the (variable) smartphone and software costs.

3.3. Children 24 months to 12 years

3.3.1. Stadiometers

Stadiometers are perhaps the most widespread method of measuring height in children above the age of 24 months. Analogue stadiometers are commercially available from many suppliers [39–42]; a typical such device is shown in Figure 1(b). Portable Stadiometers operate in a similar way to infantometers, except that the child is standing rather than recumbent.

These portable stadiometers are light, usually weighing between 1.9 kg and 2.5 kg, and can be quickly disassembled and packed into a case for easy transport. Designs between manufacturers show little variation. They do not generally meet the required temperature range (Table 5) defined in the UNICEF TPP (–10 °C to +45 °C) but cover most of the range. The operation of these devices is straightforward and does not vary significantly from the operating procedure described in the training course currently provided by UNICEF and WHO [8]. In fact, UNICEF already uses a portable stadiometer as its preferred method of child height measurement [17]. Portable stadiometers are also the most cost-effective, with a price range between the US $79 and the US $166 per unit.

Stadiometers are not suitable for use on uneven surfaces which, depending on the environment, maybe likely in LMICs. Otherwise, their accuracy, training needs and child-friendliness are similar to the portable baby/child length/height stadiometer already used by UNICEF. As these devices require manual reading and recording of height, they do not satisfy the highlighted need for automated data collection

3.3.2. Laser height measurement

Laser distance measurement is a reliable method for determining distances and is used in many industries. There are a number of prototypes for laser height measurers that have been reported in academic journals.

Schrade and Scheffler [44] developed a prototype for a laser height measurer by incorporating a commercially available laser rangefinder [45] into a right-angled accessory. To measure standing height, the device is first placed on the floor to determine the distance from the ground to the ceiling, then placed on a subject's head to determine the distance from the crown of the head to the ceiling. The subject's height is determined by subtracting the two distances and the resulting standing height displayed on the screen of the laser rangefinder. Mayol-Kreiser et al. [46] developed a similar device using a laser rangefinder [47]) attached to a metal plate with two levels (Figure 4(a)). The device is placed on the subject's head and the operator uses the levels to ensure that the device is correctly positioned. Instead of using the difference of distances method, the device directly measures the distance from the crown of the subject's head to the floor/ground.

Bauman et al. [48] developed an adapted laser measurement tool called the Anthropometric Measurement Assist (AMA) and compared the measurements to those recorded with a traditional measurement board. The AMA consists of a right-angled board placed on top of the head of the subject and a laser rangefinder, which is placed on the ground in front of the subject. The device then measures the distance from the ground to the headboard, taking that value as the subject's height. The system cost the US $179 (2018), thus within the US $300 price range set in the UNICEF TPP. The authors found no statistically significant difference in the accuracy of measurements between the AMA or the measuring board but noted that the laser measurement tool "slightly and consistently" underestimated the subject's height, for which a correction factor can be applied. This approach is similar to the laser measurement tool used by Mayol-Kreiser et al. [46], except that the laser rangefinder is placed on the ground and the measurement is made from ground to headboard rather than from headboard to ground. The Bauman et al. [48] approach is preferable because it is easier to hold the laser range finder still and in the correct orientation on the ground rather than at the top of a moving child's head.

Sørensen et al. [50] investigated the use of a novel portable laser height metre and measured its performance against the results of a standard wall fixed stadiometer [57]. Although the subjects in this study were not children, the device could be applied to measuring child growth once the child can stand. A Bosch Zamo laser rangefinder [51] is mounted perpendicularly to the end of a wooden board (Figure 4(b)). The device is then placed on top of the subject's head and the distance to the ground is measured by the rangefinder, taking that distance as the subject's height. The authors cite a price of €70 (2020) or approximately US $83 excluding the Bosch Zamo device.

These laser devices are generally compact, light (between 0.5 kg and 0.8 kg), can be easily transported and can operate within the desired temperature range and environmental conditions. Unlike traditional stadiometers, however, they do not splash- or waterproof (i.e., the laser finder must not get wet). The laser rangefinders themselves are highly accurate with measured errors between ±1 mm and ±3 mm (Table 5), meeting the ±3 mm minimum threshold set in the UNICEF TPP. The prototypes are easily manageable and require little training for operation. In the case of Mayol-Kreiser et al. [46], the device was shown to be used correctly even by an untrained operator. The device is child-friendly, requiring no restraining, measurement is instantaneous and, in the cases, where the rangefinder is attached to the headboard (all except Bauman et al. [48]) can be carried out by a single operator. The devices require that the subject stand against a vertical wall to allow for correct body positioning, which may not always be feasible. The potential limitation of these systems is the costs associated with the laser rangefinders. The cost of the laser rangefinders used in these prototypes range from the US $66 to the US $360, which would make the entire assembly cost over the desired price, but a less expensive, and probably less accurate, rangefinders can be replaced in the assembly to bring the price down. Although there is a lesser chance of read off error because of a digital readout, the chance of recording errors is not mitigated by this technology.

In terms of commercially available laser height measurers, two are currently available on the market [52,53]. Both of these operate fairly similar in that they are placed on the head of the subject and the device

Table 5. List of child growth measurement devices and specifications used for children above 24 months.

Product name	Dimensions (cm)	Mass (kg)	Temperature range (°c)	Measurement range (cm)/minimum gradations (mm) Error (mm) Test-Retest Reliability	Price (US$)
	Stadiometers				
Charder HM200P PortStad [39]	L: 35.0 W: 40.0 H: 243.0	1.9	+5 to +35	14 to 205 1 ±10 –	95.00
Seca 213 [40]	L: 59.0 W: 33.7 H: 216.0	2.5	+10 to +40	20 to 205 1 ±5 –	166.00
Marsden HM-250P [41]	L: 51.5 W: 35.0 H: 213.0	–	–	13.5 to 210 1 – –	£60.00 (79.00[a])
ADE Germany MZ10042 [42]	L: 34.8 W: 21.4 H: 41.0	–	–	15 to 201 1 – –	£100.00 (132.00[a])
Hopkins Portable stadiometer[43]	L: 61.6[c] W: 35.6[c] H: 11.5[c]	–	–	25 to 200 1 – –	89.95
	Laser height measurement				
Schrade and Scheffler [44]	L: 18.0 W: 6.4 H: 16.0	–	Measuring device is the GLM 250 VF (see below)	0.96	
GLM 250 VF professional [45]	L:12.0 W:6.6 H: 3.7	0.24	−10 to +50 −20 to +70[b]	50 to 15000 0.1 ±1 –	£359.92 (471.00[a])
Mayol-Kreiser et al. [46]	L:27.5 W:11.0	0.527	Measuring device is the GLM 40 (see below)	0.95	
GLM 40 professional [47]	L:10.5 W:4.1 H:2.4	0.09	−10 to +45 −20 to +70[b]	15 to 4000 1 ±1.5 –	£88.20 (115.00[a])
Baumann et al. [48]	L:35.6 W:2.54	1	Measuring device is the Disto D2 (see below)	0.95	179.00
Leica Disto D2 [49]	L:11.6 W:4.4 H:2.6	1	−10 to +50 −20 to +70[b]	5 to 10000 0.1 ±1.5 –	179.00
Sørensen et al. [50]	L: 50.0 W: 3.0 H: 4.0	0.8	Measuring device is the Zamo (see below)	0.99	€70 (83.00[a])
Bosch Zamo [51]	L: 10.5 W: 3.8 H: 2.2	0.08	−10 to +40 −20 to +70[b]	15 to 2000 1 ±3.0 –	£50.00 (65.50[a])
Capaltec HeightLight [52]	L: 16.0 W: 8.5 H: 2.7	0.2	−10 to +30	≥3000 1 ±1.5 –	£240.00 (317.0[a])
Kiko laser height measurer [53]	L: 8.5 W: 8.5 H: 4.0	0.083	−15 to +50	– – ±1.5 –	89.00
	Photographic				
Barros et al. [54]	–	–	–	– – – –	–
Penders et al. [55]	–	–	–	– – ±9 –	–
Liu et al. [56]	–	–	–	– – ±11 0.99	–

[a]Indicates price from manual conversion based on the exchange rate in July 2020.
[b]Indicates allowable storage temperature range if given.
[c]Indicates disassembled/folded dimensions.

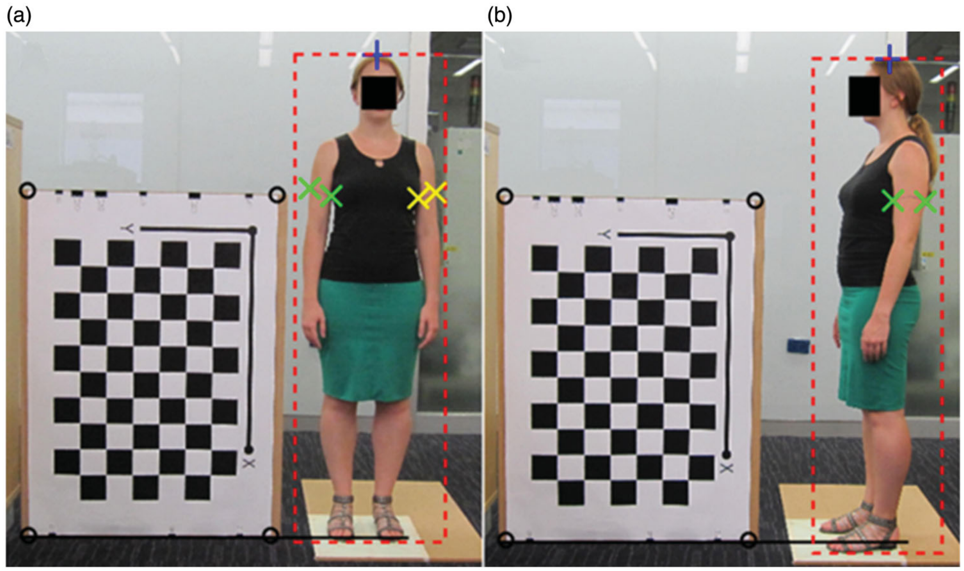

Figure 5. Images showing the positioning of the subject and digital marker placement in Liu et al. [56].

then digitally displays the subject's height. These two devices do not even require a perfectly flat alignment on the subject's head and can auto-calibrate, accounting for slight offsets in angle from unlevel device placement atop the head. The HeightLight device [52] works by triangulating its height from a laser angled at 45 degrees towards the ground, providing a digital readout of the height value. It is light (0.2 kg) and small and provides a digital read-out, however, its market price (US $317 including VAT, Table 5) is over the desired price set in the UNICEF TPP. The portable Kiko device [53] determines height *via* the same head to ceiling technique used by Schrade and Scheffler [44]. It has the added capability of directly transferring the height data to a smartphone, completely eliminating the need for data read-off and recording. The data can be stored and tracked over time using the accompanying software and directly addresses the highlighted need for automated and digital recording and data storage. Given that the Kiko device determines height using the head-to-ceiling technique, it may not be applicable in the rural context of LMICs where many poorer families live in small huts without a flat ceiling.

3.3.3. Photographic height measurement

Photogrammetry is a technique that allows for the determining of the position and shape of objects using photographs [54]. Researchers have applied photogrammetry to anthropometric measurements of different parts of the body such as hands, head and other smaller body segments, most notably for use in garment making. However, a few systems have used photogrammetry to measure standing heights in children and adults.

Barros et al. [54] measured human body segments through digital photogrammetry. Images of human body segments in different positions taken from different locations are captured using a digital camera and then fed into the computer-based Digita software capable of taking anthropometric measurements based on the position of the placed landmarks. In a study by Penders et al. [55], photographs were taken by a medical photographer with a Canon EOS 70D digital camera positioned at 4 m from the subject, with children photographed in standard anatomical position against a fixed backboard (Figure 5). Landmarks on the body were manually identified during the image processing stage, rather than by placing physical markers on the patient as in the Barros et al. [54] system. Liu et al. [56] used a single camera but took photographs from 5 different viewpoints. Distances were computed using both camera calibration and reference object techniques from manually annotated photos (Figure 5). In a similar way to Penders et al. [55], landmarks on the subject were manually identified using the image processing software. The authors do state that in future work, automatic landmark identification is a key priority for the development of this method. The study compared the photogrammetry measurements to manual measurements collected according to the WHO anthropometry training course [8] and showed good agreement with similar accuracy.

In order for photogrammetry to operate effectively, as little clothing as possible must be worn by the subject and in some cases, landmark identifiers must be physically placed on the body of the subject. The subject must then adopt certain positions in order to get useful images. These limitations may be difficult to achieve with young children (and/or in certain cultures) and will require considerable skill and patience from the operators. In addition to training in the correct positioning of the child and placing of landmark identifiers, operators must be trained in taking quality images from the correct viewpoints, amounting to extensive training needs for operators. Also, although initial image collection is *via* a portable system, the image processing in these systems is performed on a computer making the whole process not entirely portable and requiring trained computer operators. Most authors highlight this as the next phase of development and hint at the development of a smartphone App capable of on-site image processing techniques as used for children below 24 months [37,38].

4. Conclusion

This review of existing length and height measurement devices has laid the groundwork for the future development of more accurate portable devices. For children below the age of 24 months, we observed that portable infantometers or measuring mats are the most universally available devices but has been little advancement in the sophistication of these tools over the years. Although some of these devices come with digital displays, manual data recording is still required which is prone to error and therefore these devices do not comply with the UNICEF TPP. The pairing of a digital version of such devices, which would automatically transfer data to a central database, would likely much better fulfil the UNICEF TPP.

For children above the age of 24 months, portable stadiometers are the preferred measuring tool but suffer the disadvantage of requiring manual reading and recording of height data. A new and innovative photographic approach has been introduced for measuring child standing height which appears to be relatively child-friendly, but such devices appear to be far less portable, often requiring trained photographers and a computer to conduct image analysis for anthropometric data extraction. Hence these devices would be unsuitable for growth assessment in household surveys and rural health clinics in LMICs. Two commercially available laser height measurement devices have the capacity to automatically transfer height data from the device to a smartphone *via* Bluetooth. However, the high cost of commercially available devices in this category would limit the applicability of their use in rural settings in LMICs. Therefore, further developments in low-cost, portable laser devices to make them appropriate for use in LMICs are needed, to improve data quality in nutrition and health surveys, as well as the diagnostic value of routine assessments in clinical settings to monitor an individual child over time.

The findings of this review identified a large gap in the product market with respect to devices that can automatically record and transfer length or height data to a central database. Even in cases where the data are stored automatically, the issue of child-friendliness is not appropriately addressed in current devices, particularly regarding the requirement for the operator to straighten the infant's legs. Therefore, future development of child length and height measurement devices should focus on addressing these issues.

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