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Optimizing a determination of chewing efficiency using a solid test food

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Abstract

A test using a solid food is relevant to measure chewing ability (CA) as (a) it includes an integrated functioning of all oral structures involved, (b) an impairment of chewing a solid food causes inevitably diet restrictions, and (c) chewing efficiency (CE) can easily be defined. CE is the number of chewing cycles, *N(1/2-Xo)*, needed to attain a particular chewing outcome (a median particle size, X_{50}, which is half the initial particle size *Xo*) whereas chewing performance (CP) is a state of chewing outcome (X_{50}) at an arbitrary number of chewing cycles. The use of CE is preferable for CA because inter-subject ratios are constant regardless of the initial conditions of the test food. Furthermore, the inter-subject variation is two times larger for CE values than for CP ones, yielding a better inter-subject differentiation of CA. However, a determination of CP needs only one *N*-value, and that of CE at least two *N*-values for enabling an interpolation of *N(1/2-Xo)*. Using samples of only two half-cubes (9.6 x 9.6 x 4.8 mm; limiting test load) of Optosil (an artificial test food), and detailed previous information on $log(X_{50})$-$log(N)$ relationships (Liu et al., *Archives of Oral Biology*, 2018, 91, 63–77) as a "gold standard," a short procedure has been developed for a priori choosing two appropriate *N*-numbers, and the subsequent determination of a subject's CE. This procedure has been developed using results from 20 young adults (23.7 years, *SD* 1.1) and was validated in 10 middle-aged and older adults (52.3 years, *SD* 10.1), where impairments in the dentition were reflected in the CE-values. Our short procedure to determine CE will improve studies on relationships between CA and food preference, or between CA and dental factors and/or physiological factors. The first type of relationship may be of interest for food industry whereas the second type may be of interest for population studies in rapidly aging societies and for clinical studies in dentistry. Results can be compared between subjects and studies without bias by using CE rather than CP as a measure of CA.

KEYWORDS
age, chewing efficiency, chewing performance, food comminution, mastication, tooth loss

1 | INTRODUCTION

In order to measure chewing ability (CA), chewing tests have been developed using a soft bolus made of a color-changeable or two-colored chewing gum (Komagamine, Kanazawa, Minakuchi, Uchida, & Sasaki, 2011; Schimmel, Christou, Herrmann, & Müller, 2007), or wax (Sato et al., 2003; Speksnijder, Abbink, van der Glas, Janssen, & van der Bilt, 2009). Such tests have been used in patients whose CA is extremely impaired, for example, in stroke patients (Schimmel, Voegeli, Duvernay, Leemann, & Müller, 2017) or in patients following surgery and/or

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radiological treatment for intraoral oncological issues (Speksnijder, van der Bilt, Abbink, Merkx, & Koole, 2011). However, such tests have disadvantages, in particular, when they are applied in subjects whose CA is less impaired or non-impaired. First, the chewing task may be so easy that the test differentiates less optimal between subjects (Shupe, Resmondo, & Luckett, 2018). Second, tests using colored chewing-gum or wax measure a subject's ability of mixing a semisolid artificial test food between the teeth, or between tongue and palate, rather than an integrated functioning of all oral structures which are involved in the breakdown of solid foods. Third, all such tests measure chewing performance (CP; a state of chewing outcome following a particular number of chewing cycles) rather than chewing efficiency (CE; the number of chewing cycles needed to attain a particular chewing outcome; Bates, Stafford, & Harrison, 1976; van der Bilt, Olthoff, van der Glas, van der Weelen, & Bosman, 1987), which is preferable (see below, cf. Section 4). A test using a solid food is relevant as (a) it includes all aspects of food comminution during chewing (transport and capturing of particles during each cycle following breakage, mixing with saliva), (b) an impairment of chewing a solid food causes inevitably diet restrictions, and (c) it is easy to define a measure of CE.

The comminution process is reflected in the reduction of the median particle size (X_{50}) with the number of chewing cycles (N). CP is quantified by an X_{50}-value following a particular number of chewing cycles, $X_{50,N}$ and CE by the number of cycles needed to achieve an X_{50}-value that equals half of the initial particle size, *N(1/2-Xo)* (van der Bilt et al., 1987). A larger CP corresponds with a smaller value of $X_{50,N}$, and a larger CE with a smaller value of *N(1/2-Xo)*. The use of CE is preferable as a measure of CA because, in contrast to CP, CA between subjects is compared at the same stage of food comminution. The inter-subject ratios between values of CE are then constant regardless of the initial conditions of the test food (Liu, Wang, Chen, & van der Glas, 2018). Furthermore, the inter-subject variation of values of CA is two times larger for CE than for CP. Hence, CE yields a better differentiation of CA between subjects.

CE has a disadvantage: a determination of a subject's CP needs only a single number of N, whereas a determination of CE needs more numbers of N (at least two) for enabling an interpolation of *N(1/2-Xo)* within a range of different $X_{50,N}$-values at these N-values. However, the risk on a heavy test load for CE can be diminished, first by considerably shortening the chewing sequences needed. To that end, optimal conditions have been determined in our previous study for the shape and number of particles in the initial particle samples (Liu et al., 2018). By using only two half-cubes (9.6 x 9.6 x 4.8 mm; sample volume: 0.88 cm^3) of the artificial test food Optosil, apart from short chewing sequences, the amount of bite force needed to fracture the Optosil particles is reduced by 40% with respect to a traditional test (Liu et al., 2018). Hence, a potentially feasible test is available to determine CE in subjects with various degrees of impairment of CA.

A value of *N(1/2-Xo)* of CE is usually found first as a *log(N(1/2-Xo))* value in a decreasing $log(X_{50})$-$log(N)$ relationship. The initial convex shape of $log(X_{50})$-$log(N)$ relationships was revealed by using chewing sequences with four different N-numbers (Liu et al., 2018). Values of *log(N(1/2-Xo))* were accurately non-linearly interpolated. In order to facilitate population studies or clinical studies in which measurement of CE is included, the first aim of the present study was to shorten the CE procedure by enabling the use of two N-numbers (the minimum). Based on detailed information on $log(X_{50})$-$log(N)$ relationships of young adults from our previous study and the present study, a short procedure has been developed for a priori choosing two appropriate N-numbers for the determination of a subject's CE that is unknown in advance. Requirements for the range of these two N-numbers are (a) appropriate for linear interpolation (avoiding extrapolation) of the value of CE and (b) sufficiently small so that the remaining curvature of a $log(X_{50})$-$log(N)$ relationship and its effect on the value of CE, becomes negligible. The second aim of the present study was to validate the procedure for choosing N-values, by examining whether CE could consistently be derived by linear interpolation in a sample of middle-aged and older adults. This sample had variation in the number of posterior teeth present, in contrast to the young adults who all had a complete natural dentition. CE was reduced with tooth loss, in a study (van der Bilt, Olthoff, Bosman, & Oosterhaven, 1993) using a traditional procedure with large particle samples (eight Optosil cubes of 8 mm; 4.1 cm^3), which required long chewing sequences. Since a constant conversion factor is involved between studies on CE, which differ in the initial particle samples (Liu et al., 2018), tooth loss will also be reflected in a reduced value of CE from a shortened test. Hence, a valid procedure for selecting a priori two N-values for interpolation of *N(1/2-Xo)* should yield an adequate range of larger N-values, the more the degree of CE of an older subject was lower due to tooth loss.

2 | MATERIALS AND METHODS

2.1 | Subjects

The study was carried out in compliance with the Helsinki Declaration, and approved by the University Ethics Committee (Ref. no. 2018050801), being part of a larger study on the relationship between CE and physiological variables. Twenty students (10 males and 10 females) from the School of Food Science and Biotechnology and 10 supporting personnel (four males and six females) from the Zhejang Gonshang University in general, gave informed consent, and participated in the experiments. The mean age was 23.7 years (*SD* 1.1) for the students, and 52.3 years (*SD* 10.1, range 41.2–66.2 years) for the personnel. Whereas the 20 students participated in a determination of CE using three N-numbers, 5 out of 20 students were also part of eight students who participated in a determination of CE using four N-numbers in our previous study (Liu et al., 2018). Hence, these five students yielded five duplicate measurements of CE with an interval of 1 year. The 10 older adults participated in a determination of CE using only two N-numbers to validate the procedure of selecting appropriate N-values. The subjects had a good general health (no medication). Whereas the students had a full natural dentition (allowing missing third molars) with normal occlusal relationships, 4 out of 10 of the older adults had 3–9 missing posterior teeth (cf. Table 5, section 3). Subjects were excluded who had: jaw muscle pain and/or pain in the temporomandibular joint, anamnestic report of parafunctional habits such as bruxism or grinding, or disturbances (including a history, e.g., due to an accident or a third molar extraction) of intraoral or perioral sensory function.

2.2 | Chewing experiment

An outline is given on the procedures of the chewing experiment, and the basic processing of the chewing outcome. Details can be found elsewhere (Liu et al., 2018). Optosil (version 1980, Bayer), a dental impression material was used as an artificial test food. Samples with two half-cubes (9.6 x 9.6 x 4.8 mm; sample volume: 0.88 cm^3) were used in the present study. These half-cubes were prepared in brass molds (van der Glas, Al-Ibrahim, & Lyons, 2012). The ratio between catalyst (Heraeus Kulzer GmbH, Hanau, Germany) and Optosil base was 0.02477 by weight (hence 24.77 mg catalyst to 1 g of base).

As middle-aged and older Chinese subjects might be reluctant to chew Optosil, their session was started by a trial with two pieces shortly cooked carrot (firm but less stiff than Optosil) and two almonds (stiffer than Optosil), respectively. Optosil was then introduced as a harmless chewable dental material, which facilitates measurements on the particles after spitting out, and two half-cubes served for a try-out. All subjects accepted Optosil as test food.

Using samples of two Optosil half-cubes made testing CE feasible for subjects with an impaired CA. Although more trials are needed for controls without impairment (Liu et al., 2018), testing with two half-cubes was still feasible for controls, and advantageous because CEs from both types of subjects can directly be compared.

The subject was sitting upright in a comfortable chair and chewing was started on a sample of two Optosil half-cubes. Starting and ending of chewing for some cycles *N* (see below) was indicated by the observer who followed silently the number of chews using a cycle counter (appendix in Liu et al., 2018). Following chewing, the particles were spitted out in a large coffee-filter with a round bottom which was supported by a household sieve on top of a container.

Before the experiment was started, a series of labeled containers and labeled coffee-filter was prepared, according to the various numbers of chewing cycles used. During the experiment, the subjects were blinded for the labels. Furthermore, the subjects were blinded for the content of a coffee-filter by temporarily covering the filter with a stiff paper sheet.The chewing outcome belonging to a particular *N*-number was pooled across the various trials. When the same container was needed by chance, the observer carried out a fake change of containers to keep the subject blinded for the number of chews of the next trial.

Following spitting out, the chewed particles were washed, dried, and sieved (Liu et al., 2018). Values of the median particle size, X_{50}, of the particle size distribution were obtained for each number of chewing cycles by means of curve-fitting of the relationship between cumulative underweight and sieve aperture, using the Rosin-Rammler equation (Olthoff, van der Bilt, Bosman, & Kleizen, 1984):

$$Q_W^-(X) = 1 - 2^{-(X/X_{50})^b}$$

where $Q_W^-(X)$ is the weight fraction of particles with a size smaller than *X* (underweight), X_{50}, the median particle size by weight (volume), and *b*, the broadness, which is inversely related to the variation in particle size *X*.

2.3 | Procedure for a determination of chewing efficiency

When a range of, for example four *N*-values is used (previous study), then part of a subject's *log(X50)-log(N)* relationship is determined, that is, four *log*(X_{50}),*log(N)* data points of this relationship. The critical condition for the *N*-values used is that the log-value of the subject's CE *(log(N1/2-Xo))* must fall within the range of *log*(X_{50}),*log(N)* data points for enabling a determination of the subject's CE value by interpolation using curve-fitting. When this condition is met, a determination of CE can be appropriately carried out for several subjects, either by using one range of four *N*-values with a wide span or by using more ranges (for each subject a particular one), each having a smaller span of, for example, two *N*-values. The latter option is concomitant with the least test load, for the subject (reducing the total number of chewing cycles) as well as for the researcher (reducing data processing including sieving work). In order to determine the value of CE, that is, *N (1/2-Xo)* by which initial half-cubes of 9.6 mm are reduced to a median particle size of 4.8 mm, curve-fitting with a second order polynomial function (PF) was applied to the *log*(X_{50})-*log(N)* relationship, when three *N*-values were used (young adults, present study). The function value of *log(N(1/2-Xo))* was then interpolated within the range of *log (N)*-values. In experiments using two *N*-numbers (middle-aged and older adults, present study), *log(N(1/2-Xo))* was obtained generally by linear interpolation between the two *log*(X_{50}),*log(N)* data points, and occasionally by a slight linear extrapolation.

The entire *log*(X_{50})-*log(N)* relationship of a subject with less CA is shifted toward larger cycle numbers with respect to that of a subject with more CA (cf. fig. 8 in Liu et al., 2018), reflecting the lower rate of food comminution in a subject with less CA. A subject with less CA needs therefore also more cycles to attain *N(1/2-Xo)*, the value of CE. Hence, a range *N*-values has to be assessed a priori, which will be appropriate for interpolation of the value of *N(1/2-Xo)* following actual testing, while *N (1/2-Xo)* is not precisely known in advance. The range must be smaller the more the number of *N*-values is reduced, to avoid much influence from a curvature of a subject's *log(X50)-log(N)* relationship.

In order to assess appropriate *N*-values, two issues were dealt with (a) developing a method by which a subject can dichotomously be classified as a "good" chewer or a "poor" chewer to assess roughly a subject's CA in advance, and (b) gaining a nearly complete insight in the distribution of CE-values of young adults. Because of constant ratios between inter-subject CEs (Liu et al., 2018), the *N*-values needed to determine CEs for the "good" chewers among the young adults could be used as a reference for all other subjects, including those with an impaired CA. As will be explained below, the *N*-values for subjects with an impaired CA could simply be obtained by multiplying the *N*-values from the young adult "good" chewers by a factor, which reflects how much the impaired subject is a "poor" chewer with respect to the reference group of young adult "good" chewers. The method used to decide whether a subject was a "poor" chewer, was also used to assess the factor of impairment.

In order to gain a more complete knowledge about the range of CE within young adults, the sample of eight young adults in our previous study was extended to a sample of 20 young adults. Three rather than four *N*-values were used to attain a reduction in test load while a possible curvature of an individual *log(X50)-log(N)* relationship could still be accounted for by a non-linear interpolation of *N(1/2-Xo)*, using a second order PF. As the range of *N*-values is smaller when using three *N*-values rather than four *N*-values, two ranges of *N*-values were applied for reducing the risk of extrapolation in a determination of CE. One range, the one which included chewing sequences of 1, 4, and 7 cycles with 10, 4, and 2 trials, respectively, served subjects whose CA was good ("good" chewers), thus having a small value of *N (1/2-Xo)*. Another range, the one which included sequences of 2, 7, and 11 cycles with 5, 2, and 2 trials, respectively (hence shifted to somewhat larger *N*-numbers), served subjects with a somewhat less good CA ("poor" chewers in a dichotomous classification). More trials were applied for smaller numbers of *N* to ensure that fluctuations in the way that a limited number of initial particles are handled by the tongue and the teeth, were averaged out sufficiently. *N* = 4 in the chewing sequence for "good" chewers corresponds with the mean CE observed in young adults (Liu et al., 2018). *N* = 1 is smaller than the smallest *N(1/2-Xo)* observed (1.6 cycles) and *N* = 7 is a little smaller than the largest *N(1/2-Xo)* observed (7.3 cycles). Hence, while a determination of CE by interpolation was ensured for "good" chewers, a second range with somewhat larger *N*-values ensured interpolation for "poor" chewers for which *N(1/2-Xo)* exceeded seven cycles in some subjects from the present study. The use of two ranges of *N*-values in the young adults also served an exploration of a method to assess roughly a subject's CA a priori, before such a method was applied to the older subjects.

The a priori assessment of a subject's CA was based on a fast evaluation on the presence or absence of large particles following chewing during a few exercise trials. These particles were undamaged half-cubes of 9.6 mm or large fragments, which had a sieve size that is larger than 8 mm ($X \geq 8.0$ mm). Apart from *N(1/2-Xo)*, CE will also be reflected in the number of cycles that is needed to break half-cubes of 9.6 mm to such an extent that large particles ($X \geq 8.0$ mm) are no longer present. Sieving data from our previous study (Liu et al., 2018) revealed the appropriate *N*-number for a dichotomous assessment of the CA of a young adult. Samples of two half-cubes were previously chewed for 1, 2, 3, and 7 cycles, with 10, 5, 4, and 3 trials, respectively. Figure 1 shows the *N*-number after which large particles ($X \geq 8$ mm) were no longer present, as a function of the subject's CE *(N(1/2-Xo))*. An *N*-number yielding an empty sieve of 8.0 mm, which is equal or smaller than three occurred in five out of eight subjects whose CE was large, that is, *N (1/2-Xo)* ≤ 3.8 cycles, which was smaller than the mean *N(1/2-Xo)* of 4.0 cycles (Figure 1). Hence, an absence/ presence of large particles ($X \geq 8$ mm) following three chewing cycles of an exercise trial, enables a classification of a young adult as a "good" or a "poor" chewer and subsequently choosing an appropriate range of *N*-values for testing CE for each of the two subject categories. The classification "good" chewer/ "poor" chewer based on absence/presence of large particles in the sieving data at *N* = 3 corresponded with a classification of a small/large value of *N(1/2-Xo)* (large/small CE) with respect to the mean. This correspondence is not coincidentally because subjects with a smaller value of *N(1/2-Xo)* than the mean (a measure of central tendency) have more

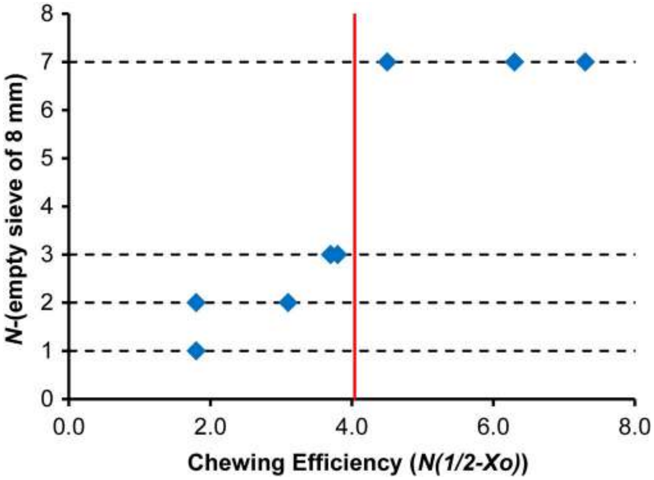

FIGURE 1 *N-(empty sieve of 8 mm)*, number of chewing cycles at which large particles ($X \geq 8$ mm) were absent, as a function of *N(1/2-Xo)*, the chewing efficiency (CE; eight subjects from Liu et al., 2018). Hatched horizontal lines, number of chewing cycles out of a series of 1, 2, 3 and 7 cycles. Red vertical line, mean CE value (4.04 cycles)

CE by definition ("good" chewers in a dichotomous classification) than subjects whose value of *N(1/2-Xo)* exceeds the mean ("poor" chewers). Figure 1 reveals the number of chews (*N* = 3) at which this correspondence can be detected by the absence of large particles in the particle size distribution.

Before actually testing CE of young adults, three exercise trials were carried out with subsequently 7, 3, and 3 chewing cycles. These trials served to accommodate the subject (in particular by the first trial with *N* = 7), and to assess the presence/absence of large particles ($X \geq 8$ mm) in trials with *N* = 3. The chewing outcomes of the trials were separately collected in coffee-filters. In an initial approach of assessment, the chewing outcome at *N* = 3 was merely visually inspected. The chewing outcomes were also digitally photographed including a size calibration, for a retrospective evaluation. When it was assessed that large particles were still present at *N* = 3 ("poor" chewer), chewing sequences of 2, 7, and 11 cycles with 5, 2, and 2 trials, respectively, were applied in the actual experiment. In the absence of large particles at *N* = 3, chewing sequences of 1, 4, and 7 cycles with 10, 4, and 2 trials, respectively, were chosen. Following the exercise trials, the trials belonging to the various *N*-numbers in the actual experiments were randomly applied.

A merely visually inspection of the chewing outcome at *N* = 3 did not optimally detect the absence/presence of large particles ($X \geq 8$ mm; cf. Section 3.3), Therefore, the detection method has been improved for the group of older adults by combining visual inspection with a quick hand-sieving of a few largest fragments, using a sieve with an aperture of 8.0 mm.

The distribution of the CE values from the 20 young adults (Table 1 in section 3.3) served to determine two ranges of two *N*-values, one for "good" chewers and the second one for "poor" chewers among young adults. Apart from a future determination of CE in young adults, the range for young adult "good" chewers served as a reference for the sequences of two *N*-values of subjects with an impaired CA (see below). The *N(1/2-Xo)* values from young adults with the best, most median, and worst CE were selected (Table 2 in section 3.3); these values were 1.69, 3.88, and 8.47 cycles, respectively. The interval of 1.69–3.88 cycles represents subjects who are "good" chewers in terms of CE (*N(1/2-Xo)* < median), but also in terms of absence of large particles ($X \geq 8$ mm) at $N = 3$, in sight of the large association between a classification as "good" chewer and each of both criteria (see above, cf. Section 3.3). The other interval of 3.88–8.47 cycles represents the "poor" chewers. The means of both intervals were 2.79 and 6.18 cycles, respectively. Upper and lower limit *N*-values were calculated around each of the interval means, using a factor of 1.5. This factor created a span of *N*-values of sufficient width for each chewer category. For example, the span for "good" chewers was sufficiently wide to include most likely the value of *N(1/2-Xo)* from any "good" chewer (classified as such according to an absence of large particles at $N = 3$), following the use of the calculated two *N*-values for this category of subjects. Furthermore, the span was sufficiently wide for overlap with the span from the other subject category, the "poor" chewers in this example. This overlap enabled a linear interpolation of CE within the interval of the "poor" chewers in the less likely but possible event (due to statistical variation in chewing outcome) of a misclassification of the subject as a "good" chewer while it was actually a "poor" chewer. On the other hand, the span was sufficiently small to avoid a large influence from the possible curvature of a subject's *log(*X_{50}*)-log(N)* relationship, which has been verified. Following digitizing of the range limits, the outcome for the sequences with two *N*-values to be used for a determination of CE, was: $N = 2$–5 for "good" young adult chewers and $N = 3$–9 for "poor" young adult chewers.

A subject with an impaired CA will need proportionally more chewing cycles to attain the same stage of food comminution at which the initial particle size is halved than a non-impaired subject. Therefore, specific inter-subject factors occur between CE-values (Liu et al., 2018), so that the *N*-values needed to determine *N(1/2-Xo)* in a subject with an impaired CA could be obtained by scaling the *N*-values from young adult "good" chewers with a multiplication factor. For example, the sequence of *N*-values for testing CE in young adult "good" chewers is 1-4-7 cycles using three *N*-values and 2–5 cycles using two *N*-values. When CE of a subject would be impaired by a factor 3, the *N*-values of testing CE must be scaled by this factor and the sequences become 3-12-21 cycles using three *N*-values, and 6–15 cycles using two *N*-values. The expected factor of impairment was derived from the presence of large particles ($X \geq 8$ mm) in exercise trials of which the *N*-number was also scaled from $N = 3$ by the same factor. For example, a subject was assigned an impairment by a factor-3 with respect to the reference group of young adult "good" chewers when large particles ($X \geq 8$ mm) occurred in exercise trials with $N = 9$, hence three times $N = 3$ used in exercise trials of young adults. Tables 3 and 4 (cf. Section 3.3) show the *N*-values to determine *N(1/2-Xo)* for various scaling factors, and procedure rules for determining the subject's appropriate scaling factor, respectively. Details and flow charts are given in the Appendix.

The validity of the procedure of selecting *N*-values was examined in the group of older adults with variation in tooth loss. Following testing CE, it appeared whether *N(1/2-Xo)* could intentionally be derived by linear interpolation between the $X_{50,N}$-values at the selected *N*-values.

2.4 | Estimating the error in a determination of chewing efficiency by linear interpolation

Rather than using non-linear curve-fitting of four *log(*X_{50}*)-log(N)* data points (Liu et al., 2018), the value of CE, *N(1/2-Xo)* may be determined sufficiently accurate by linear interpolation between two data points. When the ratio between the two *N*-values (hence the difference between two *log(N)* values) is sufficiently small, the effect of the convex shape of a *log(X50)-log(N)* relationship may become negligible.

A subject's second-order PF, which was based on four experimental data points from our previous study, was considered as an individual "gold-standard." These functions had a high quality of curve-fitting (on average $R^2 = 0.9907$, *SD* 0.0184, $n = 24$ functions: eight subjects x three types of particle samples with half-cubes). For each subject, function values of *log(*X_{50}*)* according to the PF were calculated for two discrete *N*-values which were smaller and larger, respectively, by a factor of approximately 1.5 with respect to the non-discrete value of *N(1/2-Xo)* also based on the subject's PF. A factor of about 1.5 yielded a span of the two *N*-numbers with a factor of about 2.25 (1.5^2) between these numbers. Such a span was a compromise of limiting the influence of the curvature of the *log(*X_{50}*)-log(N)* relationship, while still be able to "catch" a value of *N(1/2-Xo)* for linear interpolation in a future determination of a subject's CE. Next, CE according to a linear function (LF) through the two calculated data points from the PF describing the *log(*X_{50}*)-log(N)* relationship, was obtained by determining the intersection of LF with the level of *log(*X_{50}*)* at half the initial particle size (=log[4.8 mm]). The value of CE from LF, further denoted as *N(1/2-Xo)-LF*, was compared with the value of CE from PF, denoted as *N(1/2-Xo)-PF* (the "gold-standard"). This comparison, which revealed the influence of the local curvature of the *log(*X_{50}*-log(N)* relationship on *N(1/2-Xo)-LF*, was carried out for each type of particle sample with half-cubes, including 2, 4, or 9 half-cubes respectively (data from our previous study).

The factor of 1.5 which determined the span of the two calculated *N*-numbers on both sides of *N(1/2-Xo)-PF*, was approximated as the calculated *N*-values were rounded-off for obtaining discrete *N*-values which can be used in tests. Furthermore, the minimal *N*-value was fixed on one for the samples of two half-cubes, two for samples of four half-cubes, and three for samples of nine half-cubes. In this way, an extrapolation was avoided of calculated function values of *log(*X_{50}*)* from PF at *N*-values which would fall beyond the ranges of *N*-values used in the experiments. While the span of the range of chewing cycles used to determine PF (the range of four data points) was 7, 13, and 26 cycles for the samples of half-cubes with 2, 4, and 9 particles, respectively, the span of the two calculated data points used to determine LF was smaller, that is, on average 4.5 (*SD* 1.4, $n = 8$ subjects), 5.9 (*SD* 2.0), and 11.6 (*SD* 3.5) cycles, respectively.

2.5 | Statistical analysis

Using Excel 2010 (Microsoft), a Student's *t* test for paired observations was applied for statistical testing of differences between inter-study duplicate CE-values. Pearson's correlation was also determined between these duplicate CE-values. The level of significance was 5%. A Student's *t* test for unpaired observations was applied for statistical testing of an inter-gender difference in CE. As such a difference was non-significant, CE-results from both genders have been pooled. A Student's *t* test for unpaired observations (the variant for different inter-sample variances) was applied for testing the difference in CE between middle-aged and old subjects with a complete natural dentition and such subjects with tooth loss.

Other statistical testing need not to be presented because a change in data processing was involved, that is, a reduction in the *N*-numbers from four to two, for a determination of CE using linear interpolation. Linear interpolation versus non-linear interpolation yielded a change in the value of *N(1/2-Xo)* which occurred consistently in the same direction for the various subjects, regardless of the type of particle sample. It is self-evident that even a small change is then significant in a test for paired observations. However, the magnitude of an effect from the curvature of $log(X_{50})$-$log(N)$ relationships on linearly interpolated values of *N(1/2-Xo)* rather than the level of significance was of interest to assess whether this effect was negligible.

3 | RESULTS

3.1 | Duplicate measurements of chewing efficiency

The mean values of CE were very similar between the duplicate measurements from five young adults, that is, *N(1/2-Xo)* was 3.92 chewing cycles (*SD* 0.96; *n* = 5) in the previous study and 3.91 cycles (*SD* 2.08) in the present study. Pearson's correlation coefficient was large ($r = .931$; $p < .05$) between the duplicate CE measurements. Mean and variation were also very similar between the entire groups, that is, mean CE was 4.04 (*SD* 1.98, *n* = 8) in the previous study and CE was 4.04 (*SD* 1.87, *n* = 20) in the present study. Hence, the CE-values of the smaller sample of subjects from the previous study were representative for those of the larger sample in the present study.

3.2 | Linear interpolation versus non-linear interpolation of a value of chewing efficiency

For each subject and type of particle sample, function values of $log(X_{50})$ from a second-order PF were used to determine the parameters for a LF. CE according to LF (*N(1/2-Xo)-LF*) was compared with CE according to PF (*N(1/2-Xo)-PF* (Section 2.4).

Due to the convex shape of $log(X_{50})$-$log(N)$ relationships, values of *N(1/2-Xo)-LF* were consistently smaller than those of *N(1/2-Xo)*-PF. Figure 2 shows that the difference between LF and PF was always small, that is, less than half a chewing cycle (and constant around a mean level of only –0.2 cycles) for the particle samples with two or four half-cubes, which are of most interest for a determination of CE. Even for samples of nine half-cubes for which the negative difference increased with *N(1/2-Xo)-PF* from about 0.2 cycles to 0.7 cycles, the differences were still relatively small (on average –4%) with respect to the corresponding values of *N(1/2-Xo)-PF*.

3.3 | Choosing a range of chewing cycles to determine chewing efficiency

Table 1 shows along the ranked CE-values (*N(1/2-Xo)*; second column), the result of type-of-chewer classification of the 20 young adults from the present study, using merely an a priori visual inspection of the particles from the exercise trials with *N* = 3 (third column), and this result using a retrospective photographic evaluation with size calibration respectively (fourth column). With respect to the photographic evaluation, merely visual inspection failed to detect four cases of "poor" chewers whose degree of CE was lower than that of the mean or median.

The two ranges of the three *N*-values which were used to test CE in "good" chewers and "poor" chewers respectively (cf. Section 2.3) were sufficiently wide and had so much overlap, that the cases of disclassification had no consequences for the accuracy of the determination of CE. For example, negative consequences for the determination of CE were lacking for the extreme case of misclassification of subject S20-N as being a "good" chewer by merely visual inspection (Table 1). His value of *N(1/2-Xo)*, 6.53 cycles, falls within the wrongly chosen range of 1-4-7 cycles used for the chewing experiments. Hence, CE from all subjects was determined by interpolation within the chosen range of chewing cycles.

Although *N* = 3 was not included in the two possible ranges of *N*-values for determining CE (in contrast to our previous study, Figure 1), the amount of weight on a sieve with an aperture of 8 mm at *N* = 1 gave in retrospect a clue on the distinction between the "good" young adult chewers and the "poor" ones. *N* = 1 was applied in 16 out of 20 young adults, and the data from these 16 subjects on the weight retained by a sieve of 8 mm were distributed across two clusters (Figure 3). Normalized with respect to the mean weight of an undamaged half-cubes of 9.6 mm, the relative weight was less than that of one half-cube per trial in 9 out of 16 subjects with *N* = 1, whose value of *N(1/2-Xo)* was smaller than the median (Figure 3). In contrast, the relative weight was larger than that of one half-cube for 7 out of 16 subjects whose value of *N(1/2-Xo)* was larger than the median. The results on the absence/presence of large particles ($X \geq 8$ mm) for *N* = 4, the subsequent *N*-value in the sequence which included *N* = 1 in the present study, were in accordance with these results for *N* = 3 in our previous study (Figure 1). Thus large particles were absent at *N* = 4 for all nine subjects whose value of *N(1/2-Xo)* was smaller than the median, while fragments were still present for five out of seven subjects whose value of *N(1/2-Xo)* was larger.

Table 2 shows the derivation of the ranges of numbers of chewing cycles, when CE is determined using only two *N*-numbers, for the young adults. The ranges are 2–5 cycles for "good" chewers, and 3–9 cycles for "poor" chewers. Using a range of 2–5 cycles for "good" chewers (which is advantageous, cf. Section 4), there will occasionally be a slight extrapolation of CE on the side of two cycles, which is due to the incidence of values of CE which were smaller than two cycles (range: 1.7–1.9 cycles).

TABLE 1 Chewing ability assessed from a priori exercise trials

Subject code	Gender M/F	Ranked chewing efficiency, *N(1/2-Xo)*	Classification of chewing ability in exercise trials with *N* = 3: A priori by visual particle inspection	Classification of chewing ability in exercise trials with *N* = 3: In retrospect by particle inspection in digital images
N(1/2-Xo) < median; larger CE				
S18-N	F	1.69	Good	Good
S16-N	M	1.80	Good	Good
S03	M	2.25	Good	Good
S15-N	M	2.32	Good	Good
S06-N	F	2.46	Good	Good
S01	M	2.46	Good	Good
S17-N	M	2.83	Poor	Poor
S02	F	3.16	Good	Good
S14-N	F	3.32	Good	Good
S11-N	F	3.35	Good	Good
N(1/2-Xo) > median; smaller CE				
S19-N	M	3.88	Good	Good
S12-N	M	4.09	Good	Good
S05	F	4.39	Good‡	Poor‡
S07-N	F	4.98	Good	Good
S08-N	F	5.00	Good‡	Poor‡
S13-N	F	5.13	Poor	Poor
S10-N	M	5.36	Good‡	Poor‡
S20-N	M	6.53	Good‡	Poor‡
S04	M	7.32	Poor	Poor
S09-N	F	8.47	Poor	Poor
Median		3.61		
Mean		4.04		
SD		1.87		
n		20		

Note: Chewing efficiency (CE; *N(1/2-Xo)*) of young adults (second column). CE of subjects S01-S05, also determined previously (duplicate CE-values; Liu et al., 2018). "N" in the subject-code, "new" subject in the present study. Subject classification: "good" and "poor" chewers, based on the absence/presence of large particles (≥8 mm), detected either by visual inspection of two exercise trials with three chewing cycles (third column), or retrospectively (as a control on merely visual inspection) by inspecting photographs of the second exercise trial with three cycles (fourth column). ‡ discrepancies in classification for cases in which merely visual inspection failed to detect "poor" chewers.

Table 3 shows ranges of numbers of chewing cycles (using three numbers and two numbers, respectively), which have been scaled by various multiplication factors with respect to the appropriate ranges for young adults with an "good" CE from the present study ("good" chewers, factor-1 subjects). Table 3 also shows the number of trials needed to average out variation in the intraoral processing sufficiently and/or to have sufficient material for sieving. The total number of trials is limited to four, the more CE is impaired.

Table 4 shows the procedure rules which were successively applied to identify a subject's specific factor-line in Table 3 of which the *N*-values were used for a determination of CE. Regarding some general features: subjects were initially assigned to a low-factor level in Table 3, because less assessments of the absence/presence of large particles ($X \geq 8$ mm) were involved when a shift to a higher factor level would be needed than reversely. Furthermore, less chewing cycles were then involved. Hence, subjects who had a complete dentition at least on one side of the jaw were initially assigned to the factor-1 subjects, and subjects with much tooth loss initially to the factor-2 subjects. In total, four exercise chewing trials were carried out. Trials with an N_2-value (the procedure started with one of these) served to decide whether a subject belonged to the factor-line of that trial in Table 3; to that end these trials were evaluated for the presence/absence of large particles ($X \geq 8$ mm). A trial with an N_2-value, either from the same factor-line or from a line with a larger factor when the subject was shifted, was followed by at least one trial with an N_1-value. The last trial with an N_1-value, which was preceded by three other trials providing accommodation of the subject, was evaluated for the presence/absence of large particles to decide whether the *N*-values of the factor-line or those of an adjacent factor-line were used for the determination of CE. Details are given in the Appendix which includes also flow-charts (Figures 4 and 5).

TABLE 2 Ranges of two *N*-values to determine CE of "good" and "poor" chewers in young adults

Subject code	Chewing ability	CE, *N (1/2-Xo)*	Determination of an *N*-range for determining CE in "good" and "poor" chewers: Mid *N (1/2-Xo)* (mean)	*N*, factor 1.5 smaller than mid *N(1/2-Xo)* (lower limit)	*N*, factor 1.5 larger than mid *N(1/2-Xo)* (upper limit)	*N*, digit lower limit (+ *n*-trials)	*N*, digit upper limit (+ *n*-trials)	Type of chewers
S18-N	"Best"	1.69						
			2.79	1.86	4.18	2 (5)	5 (3)	"Good"
S19-N	"Median"	3.88						
			6.18	4.12	9.26	3 (4)	9 (2)	"Poor"
S09-N	"Worst"	8.47						

Note: Ranges of chewing cycles (*N*) when using only two *N*-values for determining chewing efficiency (CE), for "good" and "poor" chewers, respectively, among young adults with a complete natural dentition. Assessment of the ranges: (a) based on CE-values from subjects with the smallest CE-value, the nearly median value and the largest CE-value, respectively (cf. Table 1), two mid-values of *N(1/2-Xo)* have been derived for the range of *N*-values to be tested for "good" and "poor" chewers, respectively; (b) upper and lower limit *N*-values of these ranges have been determined by using a factor of 1.5; (c) the values of the range limits have been digitized in such a way that the rounded-off values of the decimal values are approached while creating sufficient overlap between both ranges. Between brackets: the number of trials needed to averaging out variation in the intraoral processing sufficiently and/or to have sufficient material for sieving.

TABLE 3 Number of chewing cycles recommended to determine chewing efficiency in general

	Determination of CE						
	Three numbers of chewing cycles			Two number of chewing cycles		Numbers of chewing cycles in exercise trials	
Factor-type of subject	N_1	N_2	N_3	N_1	N_2	N_1	N_2
Factor-1 subjects	1 (10)	4 (4)	7 (2)	2 (5)	5 (3)	3 (≤3) –	6 (1) –
Factor-1.5 subjects	2 (5)	6 (2)	11 (2)	3 (4)	9 (2)	3 (≤3) +	6 (1) –
Factor-2 subjects	2 (5)	8 (2)	14 (2)	4 (4)	10 (2)	6 (≤3) +	9 (1) –
Factor-3 subjects	3 (4)	12 (2)	21 (2)	6 (2)	15 (2)	9 (≤3) +	12 (1) –
Factor-4 subjects	4 (4)	16 (2)	28 (2)	8 (2)	20 (2)	12 (≤3) +	15 (1) –
Factor-5 subjects				10 (2)	25 (2)	15 (≤3) +	
Factor-6 subjects				12 (2)	30 (2)	18 (≤3) +	

Notes: Factor-number of subjects: subjects with, from top to bottom, a decreasing degree of chewing ability, the number refers to the factor of impairment. *N*, number of chewing cycles; between brackets: number of trials. Factor-1 subjects, adults with a similar CE as young adults with a complete natural dentition, whose CE is better than the median CE for young adults (*N(1/2-Xo)* < median; "good" chewers, reference group); factor-1.5 subjects, adults with a similar CE as young adults whose CE is more worse than the median CE for young adults ("poor" chewers). The number of chewing cycles used to determine CE, are scaled for the factor-2-6 subjects (all with an impaired chewing ability, "poor" chewers) by multiplying the cycle numbers of the reference group (factor-1 subjects) with the group factor. The number of cycles in the exercise trials, N_1 and N_2, which serve the a priori assessment of the presence/absence of large particles ($X \geq 8$ mm) have also been scaled with respect to those of the reference group. The larger number of cycles, N_2, by which an exercise sequence is started, has been scaled by multiplying N_1 of the reference group using a factor (n + 1), in which n is the group factor. + and – signs indicate present (+) or absent (–) large particles ($X \geq 8$ mm). The indicated combination of present and absent large particles must occur within a couple of *N*-numbers of exercise trials before a subject can be assigned to the factor category belonging to that couple.

Table 5 shows that the value of CE *(N(1/2-Xo))* of 8 out of 10 of the older subjects was obtained by an intentional linear interpolation between two *N*-numbers which were a priori selected according to the procedure outlined in Tables 3 and 4. One subject (E05) had a CE which was slightly smaller (1.9 cycles) than two cycles, the lower limit of the range of two *N*-values for "good" chewers. Another subject (E04) which was a priori attributed to the category of factor-1.5 subjects (Table 3), had a CE value (2.5 cycles) which was slightly smaller than the range edge of three cycles. Hence, although this subject was misclassified by chance as being a factor-1.5 subject rather than a factor-1 subject, the determination of the CE value needed only a slight extrapolation.

Table 5 also shows that 6 out of 10 subjects with an age range of 41–63 years, who had still a complete natural dentition, were all "good" chewers, that is, their individual CE-values were all smaller than the mean (4.0 cycles) or median (3.6 cycles) CE of the young adults. CE of these older adults was on average 2.25 cycles (*SD* 0.27, n = 6). In contrast, CE of 4 out of 10 subjects with a similar age range of 42–66 years but with tooth loss, was on average 7.33 cycles (*SD* 2.89, n = 4) which was significantly ($p < .05$) larger than the mean CE of the middle-aged and old subjects with a complete natural dentition. The subjects with tooth loss, subjects E01 and E08 in particular, had a preferred chewing side on the side with the larger number of occlusal units. However, missing occlusal units on this side, were still reflected in a larger value of CE, hence in less CA. The CE of subject E08 who had only one occlusal unit left was 4.7 times less than that of the mean efficiency of the middle-aged and old adults whose dentition was complete (4.7 = 10.6/2.25).

TABLE 4 Procedure rules for determining the impairment factor and the N-values used for CE

1. Start with the first exercise trial with an N_2-value:
   - N_2 = 6 for a subject who has a side with a (nearly) complete dentition (potential factor-1 or factor-1.5 subject in Table 3);
   - N_2 = 9 for a subject with much loss of chewing ability (potential factor-2 or subsequently a factor-3-4 subject);
   - The total number of exercise trials, n_T, should not exceed 4; n_T = 1 at this stage;
2. Evaluate the first exercise trial for the presence/absence of large particles ($X \geq 8$ mm):
   - If absent, remain on the same factor line in Table 3, and continue with point 3;
   - If present, switch to an adjacent larger factor line in Table 3, and continue with point 4;
3. If remaining on the same factor-line:
   - Carry out the second, third, and fourth exercise trials with N_1 of the factor-line, and evaluate the fourth exercise trial (n_T = 4) for the presence/absence of large particles:
     - If factor 1 and absent, apply factor-1 N-values for CE;
     - If factor 1 and present, apply factor-1.5 N-values for CE;
     - If factor ≥2 and present, apply same factor (≥2) N-values for CE;
     - IF factor ≥2 and absent, apply one level lower factor N-values for CE;
4. If switched to a larger factor line:
   - Carry out the second exercise trial with N_2 of the larger factor, and evaluate the second exercise trial (n_T = 2) for the presence/absence of large particles:
     - If absent, remain on the factor line,
       - Carry out the third and the fourth exercise trial with N_1 of this line, and evaluate the fourth exercise trial for the presence/absence of large particles:
       - If present, use the same factor N-values for CE;
       - If absent, use one level lower factor N-values for CE;
     - If present, second switch to an adjacent larger factor line in Table 3, and continue with point 5;
5. Carry out the third exercise trial with N_2 of the switched larger factor, and
   - Evaluate the 3rd exercise trial (n_T = 3) for the presence/absence of large particles:
     - If absent, remain on the factor line,
       - Carry out the 4th exercise trial with N_1 of this factor line, and evaluate the fourth exercise trial for the presence/absence of large particles:
       - If present, apply the same factor N-values for CE;
       - If absent, apply one level lower factor N-values for CE;
     - If present, third switch to an adjacent larger factor line in Table 3, and evaluate the 4th exercise trial (n_T = 4) with N_1 of this larger factor line for the presence/absence of large particles:
       - If present, apply the same factor N-values for CE;
       - If absent, apply one level lower factor N-values for CE.

Abbreviation: CE, chewing efficiency.

4 | DISCUSSION

4.1 | The use of an artificial solid test food for testing chewing ability

Optosil has been introduced by Edlund and Lamm (1980) as an artificial test food. In particular, since the introduction of curve-fitting of multiple sieve data by means of the Rosin-Rammler equation to characterize the particle size distribution (Olthoff et al., 1984), Optosil has commonly been used during the last 35 years in studies from Europe and the Americas (apart from Lepley, Throckmorton, Ceen, & Buschang, 2011; Olthoff et al., 1984; Speksnijder et al., 2009; van der Bilt et al., 1987, 1993, for other examples, see Liu et al., 2018, van der Glas et al., 2012). Optosil has several advantages to study food comminution. First, Optosil has a standardized strength and a homogenous structure, which in contrast to natural foods, is not influenced by seasonal or geographic variations. The strength and shape of Optosil particles can be modified in several standardized ways (van der Glas et al., 2012). The material strength of the stronger current version of Optosil (Optosil Comfort) can be made similar to that of the old version (1980) by mixing the base with the nonprescribed catalyst Verone. Second, Optosil, being a tasteless silicone-rubber is not affected by saliva. Hence, the material strength does not change during chewing and small particles are not dissolved in saliva while chewing, and are therefore well recovered following expectorating of the test food and the water used for rinsing the mouth. Because Optosil resists temperatures up to 120°C, the particles can easily be cleaned and dried. The loss of Optosil particles following chewing and sieving is small, on average 0.80% (Liu et al., 2018). In contrast, the loss is 20% when a natural food like roasted peanut, and sieving are used (Manly & Braley, 1950). A loss due to solution in saliva may also be substantial for gummy gelly, which have regularly been used as a test food for CA (Ikebe et al., 2011; Kosaka et al., 2016; Okiyama,

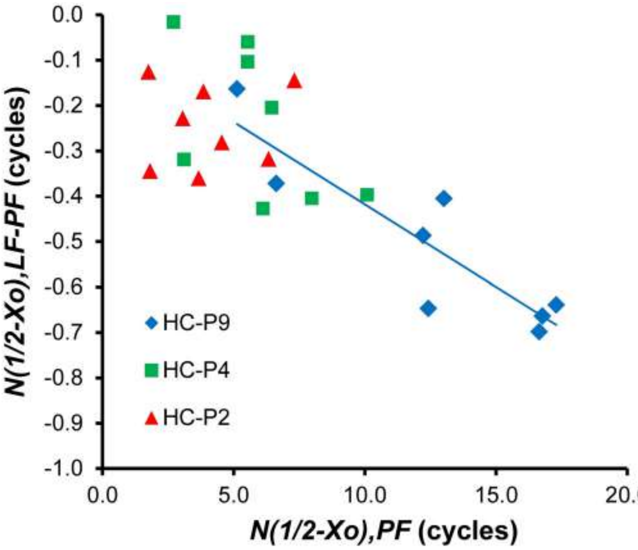

FIGURE 2 Effect of reducing the number of *log(X50)-log(N)* data points from 4 to 2 on the estimate of chewing efficiency. *N(1/2-Xo)*, LF-PF, the difference between the estimate of CE using a linear function (LF) between two data points, and the estimate using a second-order polynomial function (PF) and four data points. The difference in estimate has been depicted as a function of *N(1/2-Xo)-PF*, for the three types of particle samples of half-cubes (HC-P9, HC-P4, HC-P2, samples of 9, 4, and 2 half-cubes, respectively; eight subjects from Liu et al., 2018). Regression line: $Y = -0.0363X - 0.0546$, depicting the significant change in *N(1/2-Xo) LF-PF* for samples of nine half-cubes ($r = .892$, $p < .01$)

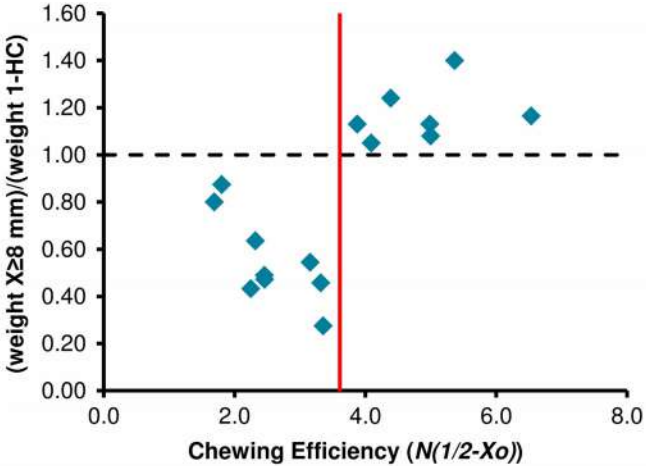

FIGURE 3 (weight $X \geq 8$ mm)/(weight 1-HC), relative weight per trial of large particles ($X \geq 8$ mm), following the first chewing cycle ($N = 1$) on two half-cubes of 9.6 mm. Data as a function of chewing efficiency from 16 out of 20 young adults who carried out $N = 1$ with 10 trials. Hatched horizontal hatched line, relative weight corresponding with that of one half-cube (HC). Red vertical line, median chewing efficiency value (3.61 cycles)

Ikebe, & Nokubi, 2003). The outcome of glucose release from the recovered gummy gelly particles, used as a measure of total particle surface area, might be biased by a previous solution in saliva during the time of chewing.

Optosil is like chewing gum a noneatable but chewable material. Optosil has been well accepted by the Chinese adult subjects from the present study, including the older adults, following a few introductory trials where chewing was started on carrot and almond.

4.2 | Validity of a determination of chewing efficiency

The mean difference between the duplicate measurements of CE from five subjects who participated in both of our studies, is extremely small and the correlation between these measurements is large ($r = .931$). Hence, a determination of CE by using particle samples of two Optosil half-cubes of 9.6 mm is highly reproducible. Four numbers of chewing cycles were used in our previous study and three *N*-values in the present study. Hence, the high degree of interstudy reproducibility indicates that the use of three *N*-values and curve-fitting with a second-order PF is sufficient to account for non-linearity of the *log(X50)-log(N)* relationships within the range of the *N*-values.

An a priori dichotomous classification of a young adult's CA as "good" or "poor" was based on the absence/presence of large particles ($X \geq 8$ mm) following $N = 3$. The results of young adults from the present study on the absence/presence of large particles are in agreement with those from our previous study (Liu et al., 2018). The weight values of large particles at $N = 1$ are divided across two clusters, that is, this weight is smaller for young adults whose value of *N(1/2-Xo)* is smaller than the median (larger CE) whereas this weight is larger for subjects whose *N(1/2-Xo)* is larger (smaller CE; Figure 3). Hence, like in our previous study (Figure 1), subjects whose value of *N(1/2-Xo)* is smaller than the central tendency (here the median) are "good" chewers in a dichotomous classification, with a larger rate of fragmentation of the large particles. In contrast, a value of *N(1/2-Xo)*, that is, larger than the median is related to a "poor" chewer with a smaller rate of fragmentation. The difference in fragmentation rate is reflected in the absence/presence of large particles ($X \geq 8$ mm) for $N = 4$, the subsequent *N*-value in the present study, that is, they are absent for all nine subjects whose *N(1/2-Xo)* is smaller than the median, while fragments are still present for five out of seven subjects whose value of *N(1/2-Xo)* is larger. This absence/presence distribution is similar to the one for $N = 3$ in our previous study. Hence, the criterion of absent/present large particles ($X \geq 8$ mm) at $N = 3$ is valid to distinguish young adult "good" chewers from "poor" chewers. Furthermore, a classification which is based on the absent/present large particles following a few (3–4) chewing cycles is related to a classification of a small/large value of *N(1/2-Xo)* (large/small CE) with respect to a central tendency (mean or median which had a short cycle distance in both studies).

Using two *N*-numbers with a span factor of about 2.25 (1.5^2), which are located on both sides of *N(1/2-Xo)* from the second-order PF through four *N*-numbers ("gold-standard"), shows that the deviation in *N(1/2-Xo)* following linear interpolation is small and negligible for particle samples of two half-cubes and four half-cubes. This deviation, on average 0.2 cycle, amounts thus about 5% of the mean CE-value for young adults, which is 4.0 cycles. Furthermore, since the

TABLE 5 Dental status, chewing efficiency (CE), and incidence of assessment of CE by linear interpolation

Subject code	Gender M/F	Age (years)	Number of occlusal units		Chewing efficiency CE: *N(1/2-Xo)* (cycles)	Attributed factor group	*N*-range tested (cycles)	$X_{50,N}$-range observed (mm)	CE linearly interpolated, $X_{50,N(1/2\text{-}Xo)}$ = 4.8 mm Yes/no
			Right	Left					
E05	M	41.2	6	6	1.9	1	2–5	4.6–2.1	No[a]
E04	F	41.6	6	6	2.5	1.5	3–9	4.2–1.8	No[b]
E02	F	42.4	6	6	2.6	1	2–5	5.4–3.6	Yes
E03	M	47.4	6	6	2.1	1	2–5	4.9–3.1	Yes
E06	F	60.3	6	6	2.1	1	2–5	4.9–2.5	Yes
E10	M	62.7	6	6	2.3	1	2–5	5.3–2.5	Yes
E01[d]	F	42.4	2	4	3.8	1.5	3–9	5.2–3.7	Yes
E07[c,e]	F	58.0	3	3	8.4	2	4–10	6.0–4.6	Yes
E09[f]	M	60.5	3	3	6.5	1.5	3–9	6.4–4.3	Yes
E08[c,g]	F	66.2	0	1	10.6	4	8–20	6.0–2.9	Yes

Note: Middle-aged and older subjects with a complete natural dentition (six occlusal units on each side) have been grouped in the top. Both subgroups have been ranked by age. Occlusal units: number of occluding antagonistic posterior teeth. An occluding molar pair corresponds to two occlusal units and an occluding premolar pair to one unit (Käyser, 1981). Third molars were excluded in the dental status. CE has been determined by using two numbers of chewing cycles according to the subject's factor group (cf. Table 3), between which the CE-value was intended to be assessed by linear interpolation.
Cases of extrapolation:
[a]Slight extrapolation for CE, 2–1.9 = 0.1 cycle, possible with *N*-range for factor-1 group.
[b]Slight extrapolation for CE, 3–2.5 = 0.5 cycle.
Dental status of subjects with an incomplete natural dentition:
Cases with a partial denture:
[c]Maxilla front prosthesis from P1 right to P1 left.
Missing posterior teeth:
[d]M1, M2 (mandible right); M2 (mandible left).
[e]P2, M1 (mandible right); P2, M1 (mandible left).
[f]P2, M1 (mandible right); M1 (maxilla right); M1 (mandible left); P1 (maxilla left).
[g]P1, P2, M1, M2 (mandible right); P1, M1 (mandible left); P1, M1, M2 (maxilla left).

deviation is consistently one-sided, it will not change the ranking of subjects according to their "gold-standard" CE-value. Hence, the use of only two *N*-values enables an accurate determination of CE of which the test duration is maximally shortened.

Using a range of 2–5 chewing cycles for "good" chewers, there is occasionally a slight extrapolation of CE on the side of two cycles, which is due to the incidence of values of CE which were smaller than two cycles (range: 1.7–1.9 cycles), in 3 out of 30 (10%) of all adults in the present study. The first chewing cycle was excluded in the cycle range 2–5 because a slight extrapolation on the side of two cycles gives less error for a few subjects (without affecting the subjects' ranking) than including a strong negative effect of curvature of a *log* (X_{50})*-log(N)* relationship for many subjects. This curvature is strongest between the first and the second chewing cycle for samples of two half-cubes (Liu et al., 2018). If included, it would affect the CE-values (obtained by linear interpolation) of the majority of the subjects whose CE falls within the range of 2–5 cycles.

In a large majority of the subjects (8 out of 10 of the older subjects, Table 5), the value of CE *(N(1/2-Xo)* was obtained by an intentional linear interpolation between two *N*-numbers which were a priori selected according to the procedure outlined in Tables 3 and 4. One subject (E05) had a CE which was slightly smaller than two cycles (1.9 cycles). However, a slight occasional extrapolation on the side of two cycles is quite acceptable when using a range of 2–5 cycles for the two *N*-numbers (see above). Another subject (E04) had a CE value (2.5 cycles) which was slightly smaller than the range edge of three cycles. Hence, although this subject was misclassified by chance (due to a limited number of exercise trials) as being a factor-1.5 subject rather than a factor-1 subject, the determination of the CE value needed only a slight extrapolation. Hence, the overlap between adjacent ranges of *N*-values (which belong to the various categories of factor-subjects), is sufficiently large to limit an extrapolation of CE that occasionally occurs, to a slight extrapolation.

Constant ratios in CE between subjects and conditions of the test food (Liu et al., 2018) enables a complete comparison between results from the present study and those from a previous study on the effect of tooth loss on CA (van der Bilt et al., 1993; reporting CP as well as CE). While samples of two Optosil half-cubes were used in the present study, samples of eight Optosil cubes of 8 mm were used previously. However, the values of CE *(N(1/2-Xo))* and the *SD*s or *SEM*s obtained with eight cubes of 8 mm can be converted to values belonging to two half-cubes of 9.6 mm by using a multiplication factor of 0.23 (*SEM* 0.011, n = 8 subjects; cf. table 2 in Liu et al., 2018).

Considering initial particle samples of two half-cubes of 9.6 mm, the mean CE of 4.0 cycles (*SEM* 0.4; n = 20) for Chinese young adults from the present study (mean age 23.7 years, *SD* 1.1), and the mean CE of 2.3 (*SEM* 0.1, *n* = 6) for Chinese older adults with a complete natural dentition (mean age 49.3 years, *SD* 9.8, *n* = 6) are similar to the converted mean CE of 3.6 (*SEM* 0.3, *n* = 32) for middle-aged subjects with a complete dentition from the Netherlands (mean age 32 years, *SD* 7, *n* = 26; van der Bilt et al., 1993). Furthermore, the non-converted mean CE of 14.6 cycles (*SEM* 4.6, *n* = 4) obtained with eight cubes of 8 mm in young Chinese male adults (mean age 23.6, *SD* 1.6, *n* = 4, Liu et al., 2018) is similar to the mean CE of 14.2 cycles (*SEM* 2.1, *n* = 8) for Dutch young male adults in another study of van der Bilt et al. (1987). The converted mean CE of 3.2 cycles (*SEM* 0.5, *n* = 8) of van der Bilt et al. (1987) is also similar to the mean CE of 3.9 cycles (*SEM* 0.6, *n* = 10) for the Chinese young male adults from the present study. Two findings are notable. First, CE is similar between Chinese and Dutch adults, despite possible differences in body size by weight or height. Second, CE is optimal for healthy adults with an age range between 22 and about 46 years (according to fairly large samples of subjects from the present study and that of van der Bilt et al., 1993), and may be optimal up to 63 years (small subsample of *n* = 6 from the present study of which all subjects were "good" chewers, Table 5), as long the adults have a complete natural dentition. These two findings suggest that an optimal CE may occur as far as the various oral functions, which contribute to CE, operate at a supra-threshold level.

Tooth loss is reflected in a CE which becomes smaller (larger values of *N(1/2-Xo)* the more tooth loss, both in the present study and in the study of van der Bilt et al. (1993). This relationship is most pronounced for the side with the least tooth loss (Table 5), which is the preferred side of chewing in subjects with tooth loss. However, the correlation between CE and tooth loss is only moderately large (fig. 3 in van der Bilt et al., 1993), which is due to the influence of other factors on CA, such as the size of the occlusal area of posterior teeth and maximum bite force at the level of these teeth (Lepley et al., 2011). The mean CE of 7.3 cycles (*SEM* 1.4, *n* = 4) for middle-aged and old adults with tooth loss from the present study (mean age 56.8 years, *SD* 10.2) is similar to the converted mean CE of 10.4 (*SEM* 2.3, *n* = 30) for middle-aged adults with tooth loss (mean age 39 years, *SD* 8) from the study of van der Bilt et al. (1993). The ratio between the mean CE values from the subjects with and without tooth loss, respectively, 3.3 in the present study and 2.9 in the study of van der Bilt et al. (1993) is also similar between both studies.

What differs considerably between the studies of van der Bilt et al. (1993) and the present study is the test load for the subjects. In the study of van der Bilt et al. (1993), a determination of CE required three trials with sequences of 60 and about 78 chewing cycles (swallowing threshold) for the subjects with tooth loss (*N* = 414 in total) and sequences of 60 and about 49 cycles for subjects without tooth loss (*N* = 327 in total). Furthermore, the use of samples of eight Optosil cubes of 8 mm (sample volume 4.1 cm^3) as a test food is concomitant with more mouth filling of particles and more bite force needed than with two Optosil half-cubes of 9.6 mm (sample volume 0.88 cm^3; Liu et al., 2018). In contrast, the present study needed in total 25 chewing cycles across seven trials for factor-1 subjects with a complete natural dentition and in total 56 cycles across four trials in the factor-4 subject with the most severe impairment of CE. Hence, using particle samples of two half-cubes of Optosil enables studying an early phase of chewing for which short chewing sequences are sufficient. Furthermore, the use of only two *N*-numbers facilitates feasibility of a determination of CE. The present study shows that accurate and reliable CE values are obtained by an a priori selection of two *N*-numbers. Including four exercise trials (6 min), the entire test (with 4–7 trials; 4–7 min) has a duration of about 10–13 min.

4.3 | Applications of a determination of chewing efficiency

Apart from testing CE in adults with varying degree of tooth loss, it would be interesting to test CE in other categories of subjects whose CA is impaired, like full or partial denture wearers, or in elderly who have dietary restrictions for other reasons than tooth loss (disability, medical, or social conditions). Many studies have reported that an impaired CA is concomitant with a selection of food for consumption, of which a soft consistency is adapted to the dental status (for a review, see N'Gom & Woda, 2002). Such a selection may yield a deficient dietary intake, which is reflected in blood-derived values of key nutrients (Nowjack-Raymer & Sheiham, 2003; Sheikam et al., 2001). Hence, studies on the relationship between CE and food preference may be of interest for food industry in sight of rapidly aging societies. The use of CE, rather than CP as a measure of CA, enables comparisons between subjects and studies without bias, due to constant ratios between CE values from different subjects and conditions of the test food (Liu et al., 2018). Furthermore, the use of a small amount of particles with initially a large particle size (two half-cubes of 9.6 mm) which requires a size reduction to 4.8 mm at CE, has two advantages: (a) less time needed for sieving (or optical scanning) because of particle size distributions where large particles predominate, and (b) a much reduced risk on choking or aspiration in subjects whose CA is largely impaired, because the median particle size at the end of the chewing sequences with two *N*-values is still fairly large. In the middle-aged and older subjects from the present study, the end median particle size varies within a range from 1.8 to 6.4 mm (Table 5). Such an end size is, in general, larger than the median particle size at swallowing (about 2 mm) of subjects whose CA is not impaired. Hence, the length of a chewing sequence is never excessively long in terms of particle size reduction, a condition to which a subject is accommodated by carrying out some exercise trials a priori. For their safety, the subjects are also allowed to spit out the particles in an "emergency" container when they would meet a problem with keeping the particles in the mouth before receiving the observer's instruction of ending chewing. However, such an event did not occur in the present study.

A determination of CE in a larger sample of elderly, than used in the present study, with some varying degree of tooth loss, would also be of interest to examine to which age CE remains optimal in the presence of a nearly complete natural dentition. Using relatively hard Optosil rather than a softer test food, for example, gummy jelly (Ikebe et al., 2011), may facilitate attaining conclusive results, as an ability to chew Optosil will be concomitant with an ability to chew a broad spectrum of similarly hard or weaker types of real foods.

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ETHICAL STATEMENTS

Conflict of Interest: The authors declare that they do not have any conflict of interest.

Ethical Review: The experiments were conducted according to the Declaration of Helsinki for studies on human subjects and approved by the Ethics Committee of the Zhejiang Gongshang University, Hangzhou, China (Ref. no. 2018050801).

Informed Consent: All participants signed an informed consent form and were compensated for their time.

AUTHOR CONTRIBUTIONS

H.G. designed and supervised the study, contributed to data analysis and interpretation, and drafted and revised the manuscript. T.L. and Y.Z. prepared and carried out the experiments, processed the chewing output, contributed to data analysis and interpretation and made comments on the manuscript. X.W. and J.C. performed fund raising, prepared facilities, contributed to data interpretation, and critically revised the manuscript.

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APPENDIX

Identifying *N*-values for a determination of chewing efficiency

The procedure which is briefly outlined in Table 4, was applied in the older adults for selecting the appropriate factor-subject category in Table 3. For subjects who have a side with a (nearly) complete natural dentition (which may belong to factor-1 or factor-1.5 subjects), the first exercise trial was carried out with $N = 6$, being the larger N_2-number of exercise trials for factor-1 subjects (see also the flow-chart in Figure 4). When large particles were absent (visual inspection and hand-sieving with a sieve of aperture 8.0 mm), it was concluded that

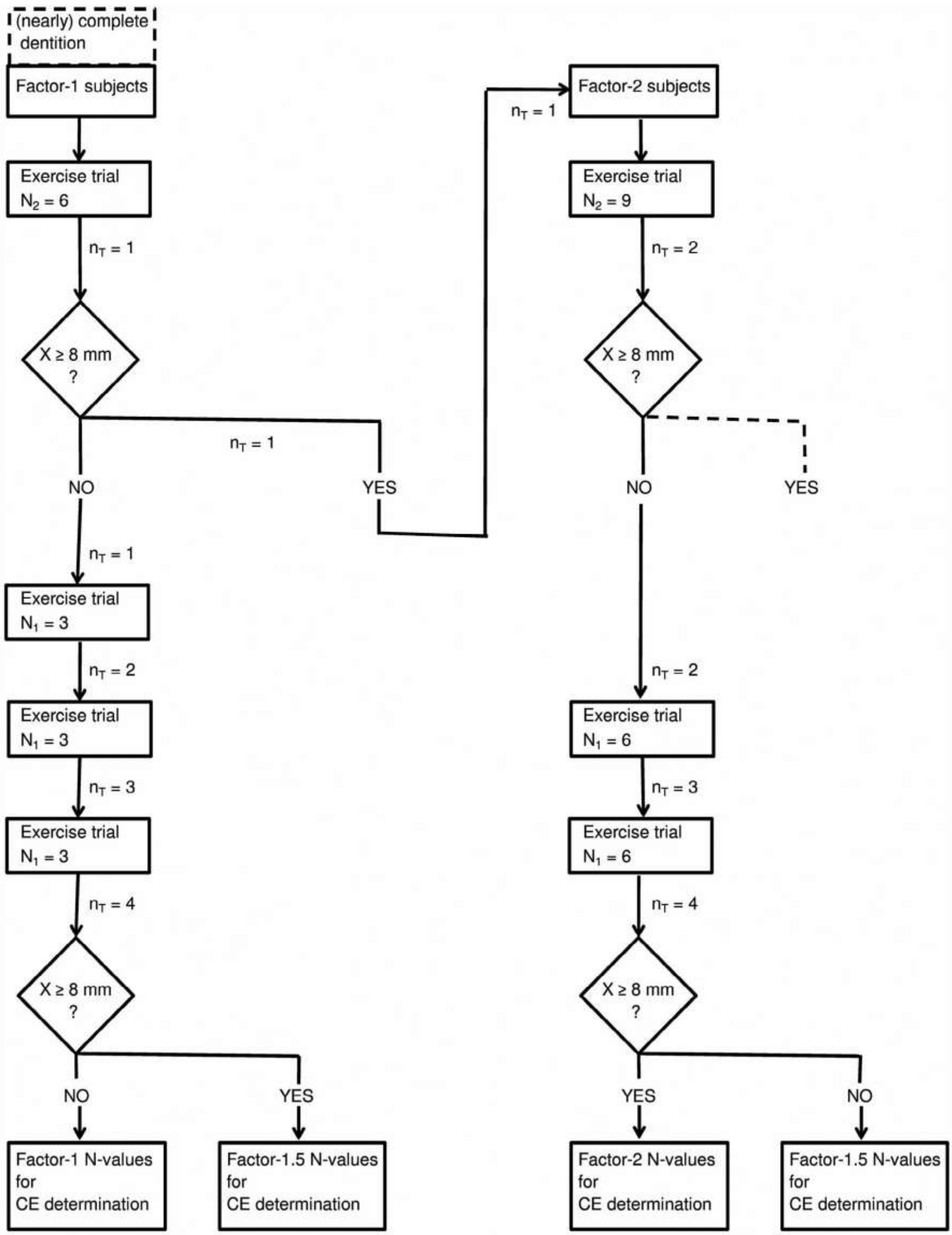

FIGURE 4 Flow chart of the procedure to find appropriate *N*-values in Table 3, which are needed to determine chewing efficiency (CE), for subjects who have a side with a (nearly) complete natural dentition. The procedure starts at factor-1 subjects here. The procedure uses exercise chewing trials of which the chewing outcome is evaluated (visual inspection and hand sieving) for the absence/presence of large particles ($X \geq 8$ mm). The total number of exercise trials (n_T) is limited to four, regardless of the path followed

the subject belonged indeed to the line of factor-1 subjects in Table 3. The smaller *N*-number (N_1, here $N = 3$) was then tested 3 times. The last exercise trial with the smaller N_1-number of a factor category was, in general, preceded by 3 other trials for ensuring a full accomodation of the subject, before this last trial was inspected for large particles. When large particles were absent, the subject continued CE-testing using the 2 *N*-numbers from the factor-1 subjects program. The subject followed the factor-1.5 program otherwise.

When large particles were present following the first trial with $N = 6$ (the N_2-number of the factor-1 line), the subject was switched to the next factor-2 line where $N = 6$ became the smaller N_1-number with one completed trial (cf. flow-chart in Figure 4). Next the trial with $N = 9$ (the N_2-number) was first carried out to examine whether the subject belonged to the factor-2 line (large particles absent) or could be switched to the next line of the factor-3 subjects (large particles present). When large particle were absent, two trials with $N = 6$ (N_1-number of factor-2 line) were carried out, of which the last one (preceded by three other trials) was inspected for large particle. When these large particles were present indeed, the subject continued the determination of CE according to the factor-2 program. Otherwise (absence of large particles, a less likely event in sight of the previous outcome for $N = 6$), the subject continued the factor-1.5 program.

When large particles were present for $N = 9$ as N_2-number for the factor-2 line (unlikely for a subject with a nearly complete dentition, but possible otherwise), the subject was switched to the factor-3 line. An N_2-trial with $N = 12$ was then first carried out to confirm a continuation of exercise trials in the factor-3 line by an absence of large particles for this N_2-number. A last trial, with $N = 9$ (N_1-number for the factor-3 line, which was, in this example, preceded by three trials with $N = 6$, $N = 9$, and $N = 12$, respectively) was then carried out to confirm the presence of large particles, so that the factor-3 program could be continued. The factor-2 program was continued otherwise.

The subject's dental status played a predominant role in choosing the starting N_2-number. For example, when many posterior teeth were missing, $N = 9$, which is critical for a decision either to try-out the factor-2 line first or to switch to the factor-3 line (Table 3; flow chart in Figure 5), was chosen, the more as $N = 9$ is a convenient small number of chewing cycles to start with. When large particle were

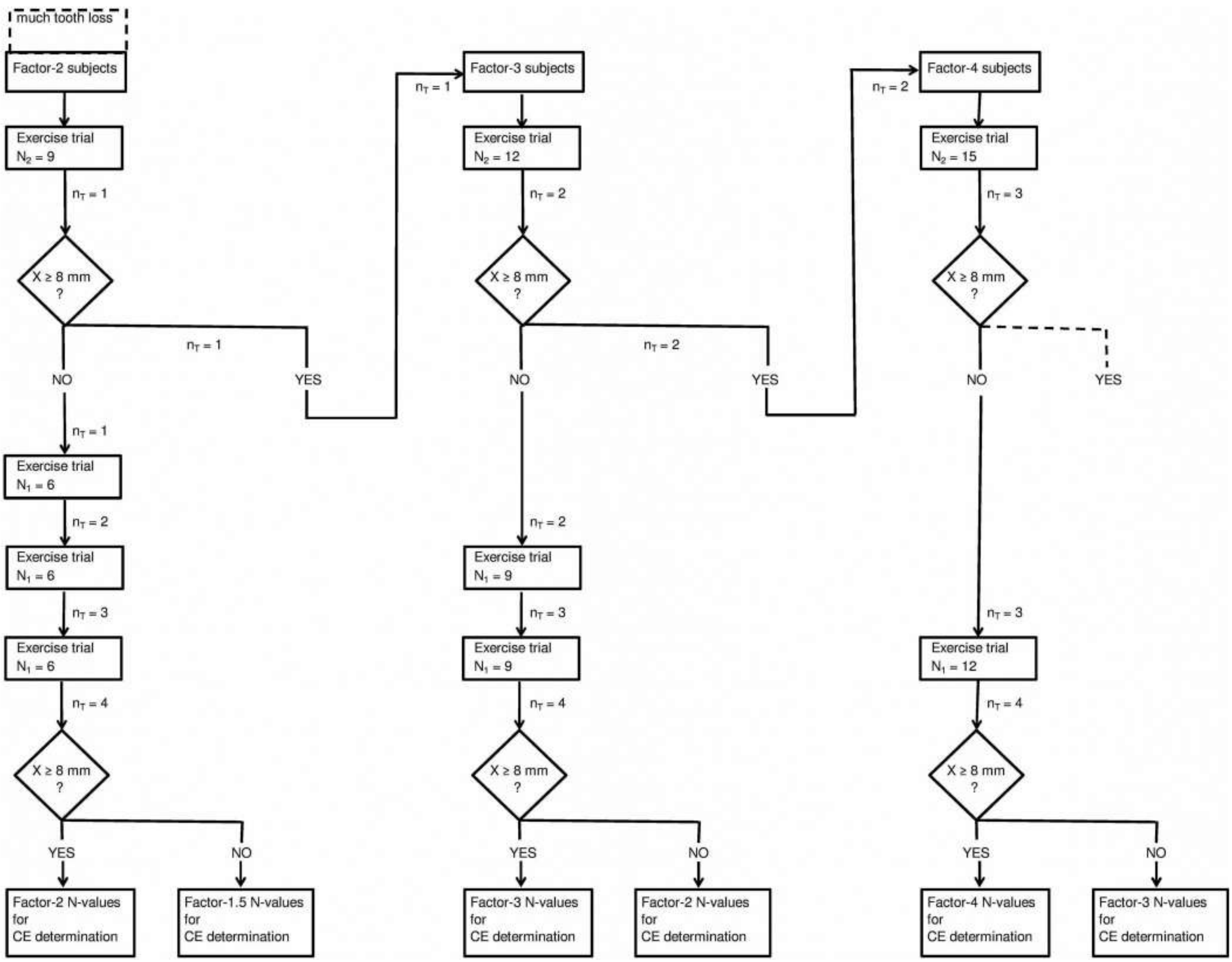

FIGURE 5 Flow chart of the procedure to find appropriate *N*-values in Table 3, which are needed to determine chewing efficiency (CE) for subjects who have much tooth loss, the procedure starts at factor-2 subjects here

present, a trial with N_2 = 12 could immediately follow to decide between the factor-3 and factor-4 line. When the factor-4 line was further tried out (because of the presence of large particles for N_2 = 12), using a subsequent trial with N_2 = 15, it is likely that large particles will be absent (because factor-4 was the end point for a subject with a largely impaired chewing ability in the present study). Following the outcome of the three exercise trials with N = 9 (positive, presence of large particles), 12 (positive) and 15 (negative) respectively, the factor-4 line could then directly by applied without carrying out a fourth trial with N = 12, thus avoiding fatigue in a subject with a largely impaired chewing ability. In general, selecting the factor category required four exercise trials at most.