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Original Article

"Fancy a Brew? ": Understanding factors influencing ease of use of cups used in care homes

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SUMMARY

Background and Aims: There are a wide variety of different designs for mugs and cups, but these are primarily driven by visual aesthetics rather than utility. The range of drinking vessels available to the care home sector is limited and not informed by ergonomic considerations that would make them more suitable for the frail elderly to use. Although our previous work has thrown some light on this problem, there is a need to improve our understanding of the ergonomics of drinking and drinking vessels to better inform both the designs available and purchasing decisions of facilities caring for older people.
Methods: This study was split into two phases, an initial qualitative focus group study and a quantitative ergonomic analysis.
Results: From the focus group study, two cups were preferred of the five presented. The characteristics shared by these two cups were lightness and large handle. From the ergonomic analysis the general grip observed in this to hold a cup can be classified as a power grip with an adducted thumb. Cups with a relatively low mass (m), a handle orifice area (S) sufficient to allow a minimum of two fingers to pass through comfortably whilst offering the ability to be supported by an adducted thumb and ring finger comfortably are seen to perform best. Further, whilst the handle orifice area should be sufficiently large for the optimal grip to be used it should also minimize the moment on the user's wrist. Computed finger forces show considerable variability across the fingers and across

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the cups. All the forces calculated from the simulation are relatively low for power grips of the type described earlier. This indicates that the individual finger grip forces are less of an issue for users than the stability needed to control and balance the force in the wrist.
Conclusion: This study has also shown that there are several critical dimensions for the design of cups for people with reduced strength and dexterity. The mass of the cup (m), the diameter of the cup D, the handle length L, and the orifice area S effecting the critical moment on the wrist and the ability to support this moment through the fingers.

Introduction

Older people are particularly vulnerable to developing dehydration due to physiological changes associated with ageing. This includes deterioration in kidney function, not recognising a sense of thirst, and a reduction in muscle mass where most water in the body is stored [1]. In addition, some older people's ability to obtain and consume fluids may be influenced by other factors such as a decline in physical health (e.g., arthritis or poor mobility), cognitive impairment, and/or swallowing difficulties (dysphagia).

The consequences of dehydration can be severe and include delirium, falls, constipation, urinary and respiratory tract infections, and admission to hospital [2]. Dehydration has also been suggested as a contributory factor in the increasing number of bloodstream infections caused by *Escherichia* coli as these infections are predominantly associated with urinary tract infection in older people and the number of cases significantly increases in summer months [3].

Adults should consume at least 1500ml of fluid per day, with the European Food Safety Authority recommending a minimum of 2000ml/day for women and 2500ml/day for men [4]. Ensuring that frail older people consume these minimum amounts of fluid each day can be challenging. Research by Wilson *et al.*, in a residential care home setting has found that many residents were chronically under hydrated, consuming less than the minimum daily requirement [3,5]. Routinely available drinking equipment, widely used in health and social care settings, has been found to be not suited to the needs of many frail older people., with cups that are difficult to hold or disliked by residents [3,6]. Further, problems with handling them may be exacerbated by underlying conditions such as muscle weakness, arthritis, or tremors. However, this is a poorly researched area which has only addressed how design can be used to overcome the visuospatial challenges experienced by people with Alzheimer's disease [7].

Bak *et al.*, [8] tested the opinions of 37 residents with respect to drinking vessel design using a Likert scale methodology. The analysis suggested that the residents' perception of a vessel's weight and volume are influenced by the ease with which they can handle the vessel. When a lightweight, high volume and easy to handle mug was introduced, the volume of fluid that residents consumed and their ability to drink independently increased, and staff were able to serve a greater volume of fluid without increasing their workload [8]. These perspectives of older people might help to inform the design of drinking vessels that enable older people to independently sustain optimal hydration and reduce their risk of adverse health effects associated with dehydration. However, the range of drinking vessels available to the care home sector is limited and purchasing decisions are generally not informed by consideration of how their design might make them more suitable for the frail elderly to use. There is a need to improve our understanding of the ergonomics of drinking and drinking vessels to better inform both the designs available and purchasing decisions of facilities caring for older people.

The aim of this study is to better understand and define the critical parameters of drinking vessels, by developing a more in depth understanding of the perspectives of those using them and quantitative measurements that describe the relationship between cup design and ease of handling.

Materials and methods

This study used a mixed methods approach split into two phases, an initial qualitative focus group study and a quantitative ergonomic analysis. Project ethical approval was granted at both The University of West London and Sheffield Hallam University and COVID-19 safety regulations for the ergonomic study were approved by Sheffield Hallam University.

Focus group study

Sample and Setting: Two focus groups were held at an Age UK day centre in West London in January 2020. The day centre provided activities for older people in the local area, who were collected and brought to the centre and attended for one or more morning or afternoon session each week. To be able to attend the day centre, they needed to be continent, require limited assistance to support mobility and not have significant cognitive impairment. Focus group participants aged between 65 and 97, were recruited from attendees to the day centre and informed consent was obtained. The focus groups were conducted using a ‘tea party’ format with the research team providing a mixture of cakes, biscuits and snacks and offering the participants drinks including tea, coffee, juice or squash.

Data collection

Five drinking vessels were provided for participants to use during the focus group; these were selected to represent different weights, dimensions and types of handle. A semi-structured topic guide was used to explore participants perceptions of the design and ease of handling of the drinking vessels and specific features that influenced their perception of the vessel. At the end of the focus group discussion attendees were asked to rank the drinking vessels according to pre-defined characteristics, e.g., weight, material, handle shape, ease of handling. The focus groups lasted approximately thirty minutes and were audio recorded to enable transcription.

Ergonomic analysis

The drinking vessels used in the focus group study were then subjected to an ergonomic analysis. The original workplan had been to undertake this *in-situ* however, the restrictions to travel and assembly imposed by the COVID-19 pandemic in March 2020 meant that changes had to be made to the work plan. To that end a Grip Analysis (including hand anthropometrics), Analytical Analysis, Finite Element Analysis (FEA) and Design analysis were undertaken with the same drinking vessels in a laboratory setting.

Grip Analysis and hand anthropometrics

A significant amount of research has been undertaken on the study of human grip taxonomies [9,10]. Each grasp can be classified by its need for precision or power to be properly executed [11]. The differentiation is very important and was further developed by Landsmeer [12], who distinguishes between “power grip” and “precision handling.” In the power grip, there is a rigid relation between the object and the hand, which means that all movements of the object must be evoked by the arm. For precision handling, the hand can perform intrinsic movements on the object without having to move the arm [12]. A third category, the intermediate or link grasp [13], was later added. In this class, elements of power and precision grasps are present in roughly the same proportion. This allows for a finer differentiation of grasp types; nevertheless, the basic principles remain the same.

There are three basic directions relative to the hand coordinate frame, in which the hand can apply forces on the object to hold it securely [14]. They differ in terms of the force direction that is applied between the hand and object [15].

Pad Opposition occurs between hand surfaces along a direction generally parallel to the palm. This usually occurs between volar (palmar) surfaces and the fingers and thumb, near or on the pad with examples including holding a needle or a small ball. *Palm Opposition* occurs between hand surfaces along a direction generally perpendicular to the palm with examples including grasping a large hammer or screwdriver. *Side Opposition* occurs between hand surfaces along a direction generally transverse to the palm here examples include holding a key between the volar surface of the thumb and the radial sides of the fingers or holding a cigarette between the sides of the fingers.

For our study to understand grip taxonomies for each cup type and to enable the research team to undertake a computer modelling analysis, we had to establish a typical grip used for each of the five cups chosen for this ergonomic study. Hence a 78-year-old independent living female (part of one of the researchers 'support bubbles') was asked to hold and drink from each cup with their grip photographed to document the grips style. A photograph of the participant holding one of the cups is shown in Figure 1.

Analytical and Finite Element Analysis

Simple mathematics allows us to analytically understand the forces on the user's hand/wrist as they hold the cup. Figure 2a shows a schematic diagram of a user holding a cup where; *mg* is the force generated by the mass of the cup (m) and gravity (g), the distance to the wrist (x), R_x the reaction force at the wrist due to supporting the cup and lastly M_x the 'moment' the cup produces on the user's wrist. Here, the term 'moment' is a physics/engineering expression describing a force acting at a distance from a point creating a turning effect.

Hence;

$$R_x = mg \tag{1}$$

$$M_x = mgx \tag{2}$$

Given that we have both measured cup mass (and computationally measured mass) we can calculate the nominal Rx and M_x as per equations 1 and 2 above. The distance x was estimated from the participants grip photos (such as those shown in Figure 1) scaled using the known geometry of the cup and from the design analysis CAD data (*mg* acting through the centre of gravity, c. o.g.) Figure 2b shows a schematic representation of the individual finger forces when gripping the cup. However, due to the large number of unknowns it is not possible to calculate the individual finger forces. Alternative methods were initially trialled such as the use of a data glove with inbuilt pressure sensors and Tekscan thin-film pressure sensors. Unfortunately, both methods proved problematic (the data glove sensors

Figure 1. Photographs of participant holding cup 1.

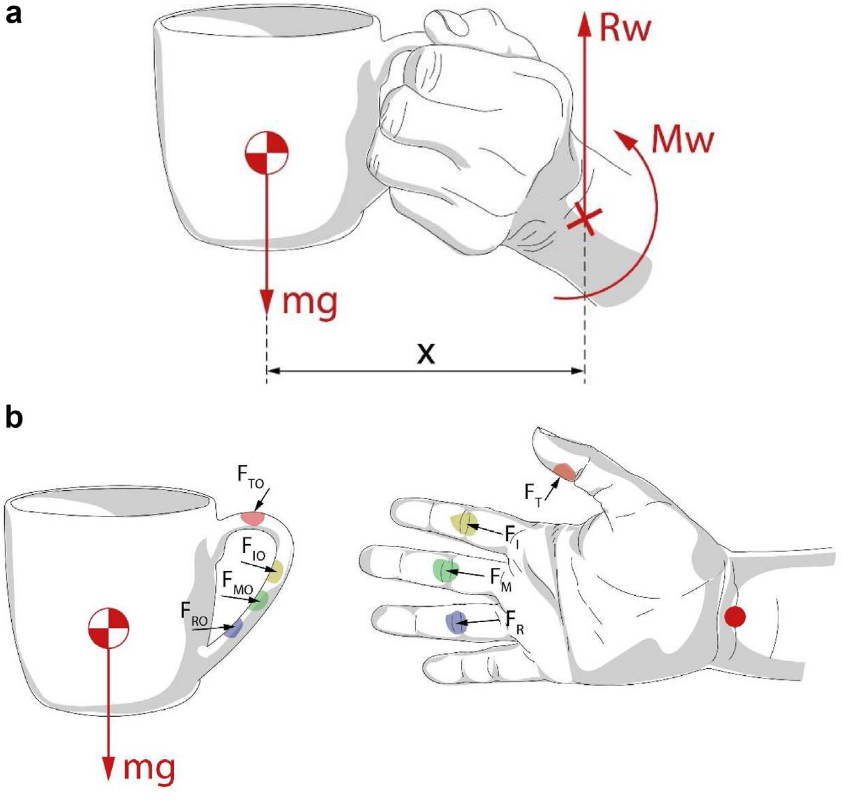

Figure 2. Schematic diagram of forces acting on the a) wrist b) fingers.

didn't match the gripping points accurately enough and the Tekscan was fiddly to fit to the cup handle. Therefore, it was decided to calculate the finger forces using computational analysis such as Finite Element Analysis.

Finite Element Analysis (FEA) is a widely used computer simulation technique; the use of which has grown rapidly with the development of computer technology. The technique works by effectively splitting the object to be analysed into discrete parts or elements which have known material properties. By applying loads and boundary conditions to represent the object's working environment and solving Newton's Laws, the deformation, stress and strain can be predicted. The object under consideration can be very broad, varying from planes and trains to, as in this case, a cup. Each cup was laser scanned and solid models created in the Computer Aided Design software, Solidworks. The subsequent 3D objects were imported into the FEA software ANSYS WorkBench. FEA is generally undertaken in 3 phases. The first phase called pre-processing, is where the geometry is set up (imported or built), the object meshed into discrete elements and boundary conditions such as loads and constraints and material properties are applied. The second phase is the processing phase whereby the computer software produces a series of matrices that facilitate the solution of Newton's Laws and hence we can understand the deformation, load, stress and strain in the object under consideration. The final phase or post-processing allows us to study the deformation, stress or strain and make understanding of the object's mechanical behaviour under the applied boundary conditions.

An example of the 3D object (in this case Cup 1) imported in ANSYS workbench is shown in Figure 3a. In this instance the water was also given physical properties but was considered a fixed solid block and results were not calculated for this material since it was added to represent the mass of fluid

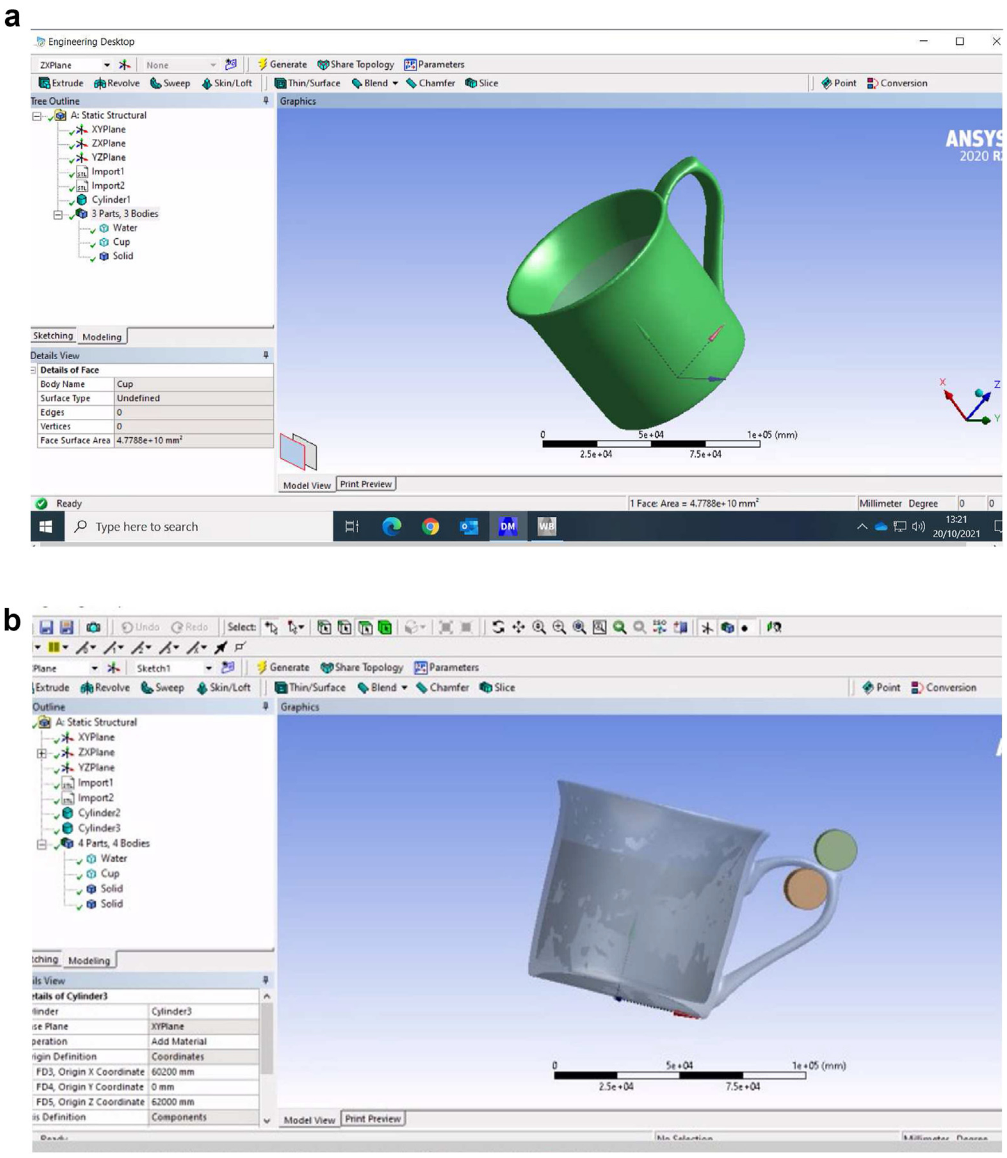

Figure 3. Imported Computer Aided Design geometry of cup 1illustrating a) calculation of reaction force b) finger placements in Finite Element Analysis.

in the cup and hence provide accurate representation for the centre of gravity (c.o.g) and subsequent reaction forces.

Using FEA, it was possible to compute the nominal reaction forces at each finger for each cup. The fingers were represented as solid rigid cylinders from which we were able to generate solutions for the reaction forces. The position the fingers was estimated from the observational analysis described above. An example of the positioning of the cylinders to represent the fingers is shown in Figure 3b.

The computational analysis calculates each force in a global cartesian co-ordinate system where (in this analysis) Y is the vertical axis, X the horizontal axis from the cup centre towards the handle (hence the XY plane cuts the cup in half through the handle) and the Z axis is at 90 degrees to this plane. Hence the total nominal reaction force for a finger (F_{Tr} for the Thumb, F_{Ir} for the index finger, F_{Mr} etc.) is then derived from combining the forces across these co-ordinates (see equation 3 below).

$$F_{Tr} = SQRT\left((F_{Tx})^2+(F_{ty})^2+(F_{Tz})^2\right) \tag{3}$$

This summation is subsequently repeated for all fingers and all cup analyses.

Design analysis

As part of the ergonomic assessment of the cups geometric features of the cup were determined from the laser scanned CAD data.

- cup mass (m)
- cup height (H)
- cup diameter (D)
- Handle orifice area. (S)
- Maximum length of handle

This design analysis allows us to understand the physical differences of each of the cups and make a comparison. As part of the design analysis, we were also able to determine the centre of gravity (c.o.g.) of each cup from the CAD data both with and without 200ml of water. Determining the c. o.g. is useful as it is the point through which the gravitational force acts on the cup. These dimensions for each cup are shown schematically in Figure 4.

Results

Focus group

In total nine participants took part in two focus groups (n=4, n=5), all participants were over the age of sixty-five and 7 were female and 2 male. The drinking vessel ranked highest on the first-choice preferences was Cup 1 (4/9) but if second choice preferences were included then both Cups 1 and 3 were ranked equal highest (6/16). It should be noted that 2 participants did not rank beyond 1st choice. The characteristics shared by these two cups were lightness and large handle, with a slight lip at the edge preferred on Cup 1 and the large size of Cup 3 (see Table 1).

Grip Analysis and hand anthropometrics

The different grip styles for each cup tested in the focus group are shown schematically in Table 2, along with a comparison to the taxonomies described by [16]. Examining previous literature, and the classifications described we can describe the grips used for holding the cups as a grip taxonomy number 5; an adducted thumb, power grip (light tool use). The main differences between every grip used for each cup is the number of fingers gripping the cup handle and subsequently the finger used to support the cup weight which is balanced by an adducted thumb (i.e., thumb in line with the hand). The variation in finger support appears to be a function of the handle size and area through which the fingers can fit.

Analytical and Finite Element Analysis

The computed reaction forces F_{Tr}, F_{Ir} etc., (for each cup are shown in Tables 3 for each direction and calculated reaction force. The finger forces show considerable variability across the fingers and across the cups. For example, Cup 3 which was highly liked by participants has a total reaction force of 16.78N

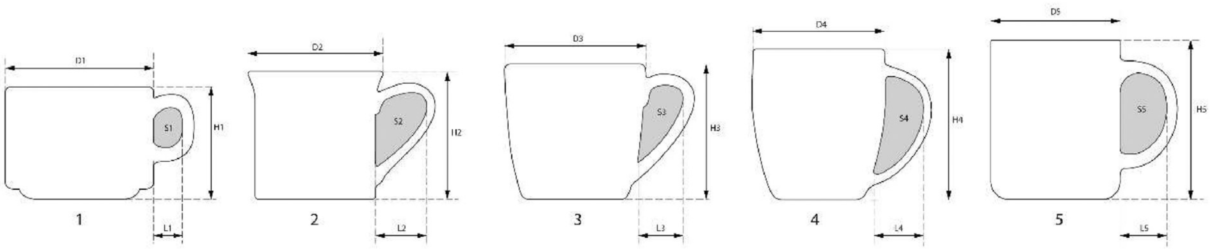

Figure 4. Schematic diagram of cup dimensions (diameter of the cup D, cup height H, handle length L and orifice area S).

Table 1
Drinking vessel ranking results

	Cup 1	Cup2	Cup3	Cup4	Cup5
					
Material	Bone China	China	Bone China	China	China
Weight	178	323	209	383	226
Rank	1	3	2	4	5
1st Choice (n=9)	4	1	3	1	0
2nd Choice (n=16)	6	2	6	1	1
Likes	Light, big handle, easy to hold, lip on edge	Stable, large handle, good size	Good size, light, big handle, easy to hold	Lip on edge Wide Handle	Place for spoon
Dislikes	Too small	Too heavy, no lip, too thick	No lip, too big	Heavy, too small, thick at top	Heavy, small handle, difficult to hold

Note: 2 participants did not rank beyond 1st choice.

whilst Cup 5, which was disliked participants, had a total reaction force of 12.14N similar to the other cups studied. An example of the results obtained from the FEA is shown in Figure 5. All the forces calculated from the simulation are relatively low for power grips of the type described earlier. This indicates that the individual finger grip forces are less of an issue for users than the stability needed to control and balance the force in the wrist. Cups that had the lowest wrist forces and allowed the wrist force to be balanced across a minimum of three fingers performed better than those that had larger moments on the wrist and facilitated poor control.

Design analysis

The five selected cups were laser scanned using specialist software. This facilitated the creation of the exact geometry and dimensions of the cups and allowed the research team to locate the centre of gravity of the cups (c.o.g.) both with and without 200 ml of (simulated) water. Understanding the position of the c. o.g. of the cup and water allows the researchers to understand how the load differs between each cup, with in theory a cup with a c. o.g. Furthest away from the handle will place a bigger resultant moment on the hand resisting that motion.

The difference in cup shape and handle size can be seen in the schematic diagram in Figure 6 where each cup has been drawn to scale from the CAD data and overlapped. This shows how both the shape of the handle and width (and in particular the height) of each cup varies, with Cup 5 having a significantly smaller overall handle area than all the other cups and the lowest estimated handle gripping height. This limits the number of fingers that can be placed around the cup handle, which is likely to increase the load on the thumb and supporting finger.

The critical dimensions for the design of cups for people with reduced strength and dexterity are the mass of the cup (m), the diameter of the cup D, the handle length L and the orifice area S which each effect the critical moment on the wrist and the ability to support this moment through the fingers.

Using the principles of inclusive design (designing for the weakest user) we can assume that users would have low grip strength, low wrist strength and reduced dexterity. Hence, we recommend future design of cups that facilitate a low moment on the user's wrist, allow a minimum of two fingers to pass comfortably through the handle orifice and facilitate the support of the cup either by the ring or little finger.

Table 2
Grip classification and analysis for each cup

				
Grip Style & Analysis H	Grip Style & Analysis	Grip Style & Analysis H	Grip Style & Analysis	Grip Style & Analysis L
Grip classification is type 5 'Light Tool Use'	Grip classification is type 5 'Light Tool Use'	Grip classification is type 5 'Light Tool Use'	Grip classification is type 5 'Light Tool Use'	Grip classification is type 5 'Light Tool Use'
Power Grip with Adducted Thumb	Power Grip with Adducted Thumb	Power Grip with Adducted Thumb	Power Grip with Adducted Thumb	Power Grip with Adducted Thumb
Cup is supported by ring finger	Cup is supported by ring finger	Cup is supported by ring finger	Cup is supported by little finger	Cup is supported by middle finger

Using the observed, calculated, and measured data, it is possible establish some general design considerations for drinking vessels of this type. Minimum and maximum dimensions of diameter (D), height (H), handle length (L) and mass (m) can be taken from examining the dimensions and values of the best performing cups in the focus groups study. For example Cup 3 mass (m) is 209g and its height (H) is 101.2mm whilst Cup 1's mass (m) is 178g and its height (H) 79.4mm is giving us mass design limits of 178g–209g and height design limits of 80mm–102mm, whilst the design limits range for the handle orifice area (S) can be established by the study by the Buchholz and Armstrong [17] which suggests that the minimum mean cross-sectional area for two fingers to pass through would be would have to be a minimum approximately 650 mm^2 three fingers would be approximately 950 mm^2. Hence, we can use this data to provide the nominal maximum and minimum values for these critical cup dimensions (Table 4).

Discussion

The general grip observed in this to hold a cup can be classified as a power grip with an adducted thumb. Whilst the grip used is in general the same for each cup, several key factors are seen to affect the user's ability to hold and make use of a cup effectively.

Namely.

- The mass of the cup m
- The handle orifice area S
- The distance between the centre of gravity (c.o.g.) of the cup and the user's wrist x
- The finger reaction forces F_i
- The user's wrist strength
- The users grip strength
- The users finger size

Table 3
Total reaction forces (N) for each cup

Cup	Fr (N)
Cup 1	12.12
Cup 2	12.09
Cup 3	16.78
Cup 4	12.19
Cup 5	12.14

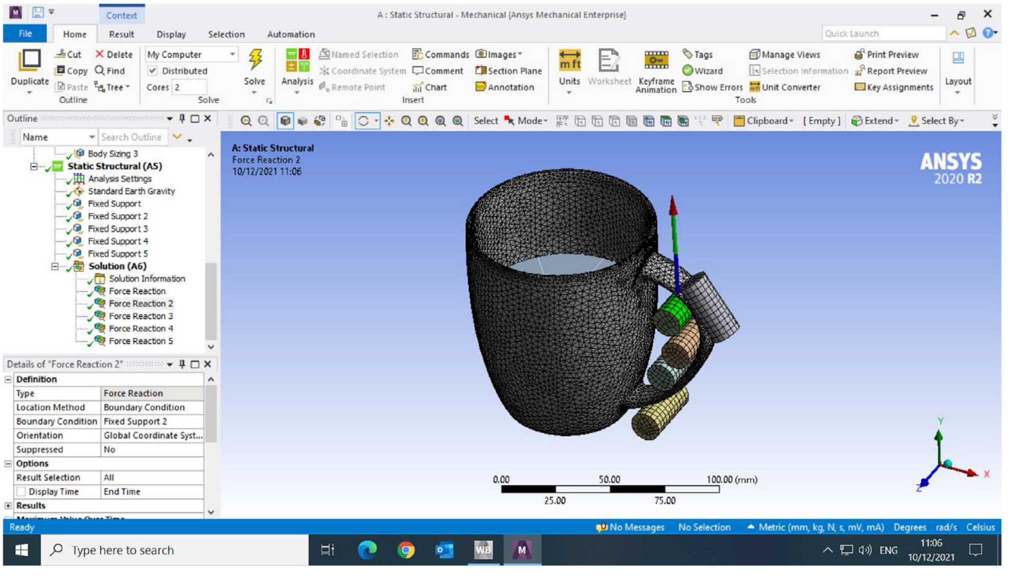

Figure 5. Example of computed finger reaction forces for Cup 3.

Cups with a relatively low mass (m), a handle orifice area (S) sufficient to allow a minimum of two fingers to pass through comfortably whilst offering the ability to be supported by an adducted thumb and ring finger comfortably are seen to perform best. Further, whilst the handle orifice area should be sufficiently large for the optimal grip to be used it should also minimize the moment on the user's wrist. Computed finger forces show considerable variability across the fingers and across the cups. All the forces calculated from the simulation are relatively low for power grips of the type described earlier. This indicates that the individual finger grip forces are less of an issue for users than the stability needed to control and balance the force in the wrist. Cups that were found to be well liked were seen to have sufficient area for the index and middle fingers to pass through the handle (supported by an adducted thumb) and subsequently helped by support from the ring finger. Work by the Buchholz and Armstrong suggests that the minimum mean cross-sectional area for two fingers to pass through would have to be a minimum approximately 650 mm^2 three fingers would be approximately 950 mm^2.

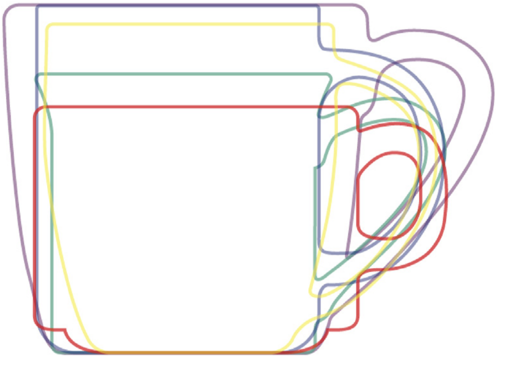

Figure 6. Overlayed schematic of cup profiles. Note: 2 participants did not rank beyond 1st choice.

Table 4
Nominal maximum and minimum dimensions for cups with reduced ergonomic loading

Cup dimension (Units)	Max	Min
D (mm)	*90*	*86*
H (mm)	*102*	*80*
L (mm)	*32*	*33*
S (mm)	*995*	*1445*
m (g)	*178*	*210*

Conclusions

There are many different drinking vessel designs on the market with a wide range of different parameters but very little data on what aspects of their design make them easy and pleasurable to drink from. The few studies that exist focus on the relationship between vessel design and the sensory experience of drinking [17] or training cups for children [18,19]. Among older people, studies that have captured qualitative data on drinking vessel preferences of care home residents [3,6] demonstrated that cups are generally not conducive to supporting adequate fluid consumption in this vulnerable population, but offering drinks in cups that are easy to hold increases their fluid consumption [8].

In this study we have aimed to understand how to improve the design of drinking vessels by linking qualitative data on features that enhance or impair the drinking experience of a group of elderly people with a detailed analysis of the critical parameters of the specific drinking vessels they used. We found that the cups that were preferred by users had the lowest wrist moment. This supports the theory proposed by Bak *et al.* [8] that a well-designed cup should have a relatively small diameter and a handle sufficiently large enough to facilitate the fingers to be passed through the orifice but as near as to the cup centre as possible to reduce the moment on the wrist.

This study has identified several critical dimensions for the design of cups for people with reduced strength and dexterity. The mass of the cup (M), the diameter of the cup D, the handle length L and the orifice area S effecting the critical moment on the wrist and the ability to support this moment through the fingers. By applying this scientific analysis to the design of drinking vessels there is a potential to make drinking equipment for the care home and other similar healthcare settings, that is easier for older people to handle and support them to consume more fluids.

Study limitations and future work

This study was undertaken at the height of the 2020–2021 COVID-19 pandemic and as such was limited in the participant facing work that could be undertaken. That said the authors feel we have a useful starting position. Going forward we aim to understand how the handle shape affects the use and perception of the cup, how the material that the cup is made of effects the cup perception and we aim to undertake a dynamic ergonomic analysis to study the loci of the c. o.g. For each cup. We also aim to undertake a critical assessment of cups available through care home suppliers and work with suppliers facilitate promotion of good cup designs where available.

Contribution

Professor Jennie Wilson, Funding acquisition, project administration, conceptualization, design, delivery and analysis of focus groups, drafting paper.

Dr Alison Tingle, conceptualization, design, delivery and analysis of focus group, project administration, drafting paper.

Professor Alaster Yoxall, Conceptualization, Methodology, Software, formal analysis, writing-original draft.

Dr John Hart, Methodology, Software.

Dr Jen Rowson, Software.

Ms Inna Lucas, Data Curation.

Conflicts of interest

There are no conflicts of interest associated with this research or its publication.

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