POMORSKI UNIWERSYTET MEDYCZNY W SZCZECINIE

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Analiza wybranych właściwości fizycznych nowoczesnych łuków ortodontycznych do leczenia aparatami stałymi cienkołukowymi, produkowanych ze stopu Gummetal

Rozprawa doktorska w dziedzinie nauk medycznych i nauk o zdrowiu

Dyscyplina nauki medyczne

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Szczecin 2021 r.

Serdecznie dziękuję mojej Promotor,

Pani dr hab. n. med. Joannie Janiszewskiej-Olszowskiej

za nieustającą motywację do pisania, zaufanie oraz bezcenne wskazówki

podczas powstawania niniejszej pracy.

Pracę dedykuję mojej Rodzinie, a w szczególności Babci Jadzi oraz Wujkowi Jankowi,

którzy zawsze stali po mojej stronie.

SPIS TREŚCI

WYKAZ SKRÓTÓW

SS – stainless steel, stal nierdzewna

CoCr – cobalt-chromium, chromokobaltowy

NiTi – nickel-titanium, niklowotytanowy

β-Ti – beta-titanium, beta-tytan

TiMo – titanium-molybdenum, tytanowomolibdenowy

Krzysztof Schmeidl

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PORADNIA STOMATOLOGII OGÓLNEJ

UNIWERSYTECKIEJ KLINIKI STOMATOLOGICZNEJ

AUTOREFERAT

SZCZECIN 2021

1. IMIĘ I NAZWISKO: Krzysztof Schmeidl

2. POSIADANE DYPLOMY, STOPNIE NAUKOWE

   06.2012 r. – Dyplom lekarza dentysty, I Wydział Lekarski, Oddział Stomatologii, Warszawski Uniwersytet Medyczny

   10.2017 r. – Dyplom specjalisty stomatologii zachowawczej z endodoncją

3. INFORMACJE O DOTYCHCZASOWYM ZATRUDNIENIU W JEDNOSTKACH NAUKOWYCH

   05.2014 r. – 05.2017 r. – Szkolenie specjalizacyjne w zakresie stomatologii zachowawczej z endodoncją w Poradni Ogólnej Mazowieckiego Centrum Stomatologii w Warszawie

   Od 01.2019 r. – Szkolenie specjalizacyjne w zakresie ortodoncji w Poradni Stomatologii Ogólnej Uniwersyteckiej Kliniki Stomatologicznej Pomorskiego Uniwersytetu Medycznego w Szczecinie

4. WSKAZANIE OSIĄGNIĘCIA NAUKOWEGO

   A. Tytuł osiągnięcia naukowego:

   Analiza wybranych właściwości fizycznych nowoczesnych łuków ortodontycznych do leczenia aparatami stałymi cienkołukowymi, produkowanych ze stopu Gummetal

Osiągnięcie zostało udokumentowane cyklem dwóch prac, w tym jednej poglądowej (przegląd krytyczny) oraz jednej oryginalnej (praca badawcza), opublikowanych w recenzowanych czasopismach, znajdujących się w bazie Journal Citation Reports (JCR).

Sumaryczny Impact Factor (IF) wynosi: 7.034; punktacja MEiN: 210

B. Autorzy, tytuły publikacji, nazwa wydawnictwa, rok wydania

1) Schmeidl, K.; Janiszewska-Olszowska, J.; Grocholewicz, K. Clinical Features and Physical Properties of Gummetal Orthodontic Wire in Comparison with Dissimilar Archwires: A Critical Review. *BioMed Res. Int.* **2021**, *2021*, 6611979. https://doi.org/10.1155/2021/6611979
   IF: 3.411; punktacja MEiN: 70
2) Schmeidl, K.; Wieczorowski, M.; Grocholewicz, K.; Mendak, M.; Janiszewska-Olszowska, J. Frictional Properties of the TiNbTaZrO Orthodontic Wire—A Laboratory Comparison to Popular Archwires. *Materials* **2021**, *14*, 6233. https://doi.org/10.3390/ma14216233
   IF: 3.623; punktacja MEiN: 140

5. POZOSTAŁE OSIĄGNIĘCIA NAUKOWO-BADAWCZE

A. Wykaz innych opublikowanych prac naukowych

1) Schmeidl, K.; Bugajska, M. Leczenie endodontyczne zęba 11 z obliteracją kanału. Opis przypadku. *Mag. Stomatol.* **2018**, 1,10-14.
   IF: 0; punktacja MEiN: 6
2) Schmeidl, K.; Bugajska, M. Urządzenia używane do aktywacji środków płuczących w endodoncji. Czy warto je stosować? *Mag. Stomatol.* **2018**, 4, 62-65.
   IF: 0; punktacja MEiN: 6
3) Bugajska, M; Schmeidl, K. Koncepcje odbudowy zębów po leczeniu endodontycznym. *Twój Prz. Stomatol.* **2018**, 6, 21-28.
   IF: 0; punktacja MEiN: 5
4) Jankowski, T.; Jedliński, M.; Schmeidl, K.; Grocholewicz, K.; Janiszewska-Olszowska, J. Sella Turcica Abnormalities, Dental Age and Dental Abnormalities in Polish Children. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10101. https://doi.org/10.3390/ijerph181910101
   IF: 3.390; punktacja MEiN: 70

B. Prezentacje zjazdowe

1) Schmeidl, K. Gummetal – nowy stop metali w praktyce ortodontycznej. W: Konferencja naukowo – szkoleniowa on-line „Nowości w stomatologii" Polskiego Towarzystwa Stomatologicznego, Oddział w Szczecinie, Szczecin, 12.12.2020 r.

6. STRESZCZENIE OSIĄGNIĘCIA NAUKOWEGO

WSTĘP

Gummetal, to stop składający się z tytanu, niobu, tantalu, cyrkonu oraz tlenu. Został wyprodukowany w 2001 roku w Japonii, w firmie Toyota Central R&D, Inc. Od niedawna jest stosowany w leczeniu wad zgryzu aparatami stałymi cienkołukowymi. Gummetal nie zawiera niklu ani chromu, które należą do alergenów kontaktowych. Według producentów, Gummetal ma wyjątkowo niski moduł elastyczności Younga, dużą sprężystość, wytrzymałość, pamięć kształtu, łatwo się dogina oraz generuje małe (biologiczne) siły, pożądane podczas leczenia ortodontycznego. Toyota R&D podaje, że siły powstałe pomiędzy Gummetalem i zamkami metalowymi mogą być do 50% mniejsze od sił tarcia powstałych przy zastosowaniu innych drutów zawierających tytan. Twierdzenia te nie mają jednak wystarczającego uzasadnienia w postaci publikacji wyników badań laboratoryjnych i klinicznych, co nie pozwala na określenie wskazań do stosowania Gummetalu w poszczególnych fazach leczenia ortodontycznego.

CEL PROJEKTU

Celem projektu była analiza wybranych właściwości drutów ortodontycznych do leczenia aparatami stałymi, wyprodukowanych ze stopu Gummetal.

W pierwszym etapie przygotowano krytyczny przegląd systematyczny piśmiennictwa, którego celem było znalezienie i usystematyzowanie wyników badań naukowych dotyczących właściwości mechanicznych i klinicznych stopu Gummetal.

Celami drugiego etapu projektu były:

1. Zbadanie wartości tarcia kinetycznego drutu TiNbTaZrO w warunkach laboratoryjnych oraz porównanie ich z wartościami stosowanych od dawna łuków ortodontycznych: stalowego, niklowotytanowego, chromokobaltowego oraz tytanowomolibdenowego.
2. Porównanie topografii powierzchni drutu z Gummetalu z powierzchnią drutu stalowego, niklowotytanowego, chromokobaltowego oraz tytanowomolibdenowego.

MATERIAŁ BADAWCZY

Krytyczny przegląd piśmiennictwa przeprowadzono przy pomocy baz PubMed, PMC, Google Scholar, Ovid oraz Cochrane Library. Wyszukiwanie prowadzono wykorzystując słowa kluczowe: *gummetal orthodontic wire* (drut ortodontyczny z Gummetalu).

Materiał badawczy etapu laboratoryjnego stanowiły druty ortodontyczne (n=50) o długości 10 cm i wymiarach przekroju poprzecznego: 0.016"x0.022" (po 10 drutów: z Gummetalu (Gummetal, JM Ortho Corporation), stalowych (Remanium, Dentaurum), niklowotytanowych (Nickel Titanium, G&H), chromokobaltowych (Elgiloy Blue, RMO), oraz tytanowomolibdenowch (BetaForce, Ortho Technology)), zamki ortodontyczne metalowe dla kła górnego prawego w preskrypcji Rotha (o rozmiarze szczeliny 0.018"x0.025") (Discovery, Dentaurum) (n=50) oraz ligatury elastyczne (Alastik Easy-To-Tie, 3M) (n=50).

METODOLOGIA PRZEGLĄDU SYSTEMATYCZNEGO I PRACY BADAWCZEJ

Do przeglądu włączano publikacje, które obejmowały podwójnie zaślepione randomizowane badania kliniczne (RCT), kontrolowane badania kliniczne, badania in vitro oraz posiadały abstrakt w języku angielskim. Odrzucono wszystkie prace, w których nie badano bezpośrednio właściwości drutu ortodontycznego z Gummetalu, przeglądy, dyskusje autorskie, streszczenia, artykuły redakcyjne, opinie oraz opisy przypadków.

W laboratoryjnych badaniach własnych każdy zamek przyklejono do stalowej płyty, a do szczeliny zamka wprowadzono badany drut. Następnie, na wszystkie skrzydełka zamka została założona nowa ligatura elastyczna, a płytkę umocowano w uchwycie przy podstawie specjalistycznej maszyny pomiarowej siły MultiTest 2.5-i (Mecmesin Ltd.), która przesuwała drut poprzez szczelinę zamka ze stałą prędkością 10 mm/min. Tarcie dynamiczne powstałe podczas automatycznego przesuwania każdego drutu mierzono w temperaturze pokojowej przez 120 sekund (1000 pomiarów na sekundę), a następnie analizowano przy pomocy specjalistycznego oprogramowania komputerowego. Do każdego pomiaru wykorzystano nowy fragment drutu, nowy zamek ortodontyczny oraz nową ligaturę elastyczną.

Topografię powierzchni drutów ortodontycznych zbadano dzięki metodzie mikroskopii różnicowania ogniskowego przy pomocy specjalistycznego systemu optycznego do pomiaru 3D Infinite Focus G5 plus (Bruker Alicona).

WYNIKI PRZEGLĄDU SYSTEMATYCZNEGO I PRACY BADAWCZEJ

Do przeglądu wyselekcjonowano ostatecznie z bazy Pubmed, Cochrane oraz Google Scholar 13 publikacji. Co zaskakujące, w piśmiennictwie znaleziono tylko jedno podwójnie zaślepione randomizowane badanie kliniczne (RCT). Pozostałe prace były badaniami drutów ortodontycznych in vitro.

Na podstawie przeglądu krytycznego piśmiennictwa stwierdzono, że druty ortodontyczne z Gummetalu posiadają niską wytrzymałość na zginanie, niską granicę zmęczenia, bardzo niski moduł Younga oraz wysoką sprężystość. Gummetal generuje większe siły od plecionego łuku Supercable, ale mniejsze niż Nitinol i stop tytanowomolibdenowy (TMA). Współczynnik tarcia stopu Gummetal jest porównywalny do współczynnika tarcia stopu niklowotytanowego i chromokobaltowego oraz, według niektórych autorów, stalowego.

W badaniach laboratoryjnych stwierdzono, że druty stalowe generowały siłę tarcia kinetycznego o średniej wartości 0.639N, niklowotytanowe 1.143N, chromokobaltowe 1.097N, tytanowomolibdenowe 1.932N, natomiast druty z Gummetalu 1.198N.

Analiza topograficzna wykazała, że powierzchnia łuków z Gummetalu nie odbiega istotnie od drutów z pozostałych stopów.

WNIOSKI

Przegląd piśmiennictwa wykazał, że informacji opartych na wynikach badań naukowych na temat drutów ortodontycznych Gummetal jest bardzo niewiele. Ze względu na nietoksyczny skład, łuki z Gummetalu mogą być stosowane zamiast łuków niklowotytanowych u pacjentów z alergią na nikiel w początkowej fazie leczenia ortodontycznego. Drut Gummetal wykazuje jednak mniejszą odporność na odkształcenia plastyczne niż druty niklowo-tytanowe, co stawia pod znakiem zapytania jego superelastyczność.

Laboratoryjne badania własne wykazały, że druty ortodontyczne ze stopu Gummetal charakteryzują wartości tarcia kinetycznego podobne do drutów niklowotytanowych oraz chromokobaltowych, wyższe od drutów stalowych, oraz niższe od drutów tytanowomolibdenowych. Niski współczynnik tarcia stopu Gummetal wydaje się odpowiedni dla mechaniki ślizgowej podczas przesuwania ortodontycznego zębów przy pomocy aparatów stałych cienkołukowych. Badanie przy pomocy mikroskopii różnicowania ogniskowego wszystkich pięciu drutów wykazało natomiast, że siła tarcia nie jest bezpośrednio związana z topografią powierzchni.

Konieczne są dalsze badania w celu oceny przydatności Gummetalu w praktyce klinicznej.

7. SUMMARY OF SCIENTIFIC ACHIEVEMENT

INTRODUCTION

Gummetal is a novel alloy, developed in Japan in 2001 at the Metallurgy Research Section of Toyota Central R&D, Inc. Recently, it has been introduced to orthodontic multibracket treatment. It consists of titanium, niobium, tantalum, zirconium, and oxygen. Nickel and chromium-free composition makes Gummetal bioinert. According to the producers, Gummetal combines extremely low Young's modulus with very high elasticity and tensile strength, which is extremely rare. At the same time, Gummetal is easy to bend, exhibits shape memory and provides low (biological) forces, which are favorable in orthodontic therapy. Toyota Central R&D states, that Gummetal wire is characterized by a lower friction between the archwire and metal brackets up to 50% compared with other titanium wires. This statement is supported by very limited research and is insufficient to provide clinicians valid information regarding indications to utilize Gummetal archwire in particular phases of orthodontic treatment.

OBJECTIVES

The aim of the present study was to investigate the advertised properties of Gummetal orthodontic archwire.

At first, a critical systematic literature review including in vitro and clinical studies was performed to verify and confirm clinical features and physical properties of Gummetal alloy.

The laboratory part of the study aimed to

1. Determine the frictional properties of Gummetal wire and compare with these of conventional wires of stainless steel, nickel-titanium, cobalt-chromium and titanium-molybdenum in vitro.
2. Perform a topographic surface comparison of Gummetal wire with stainless steel, nickel-titanium, cobalt-chromium and titanium-molybdenum wires.

MATERIAL

A critical literature review was conducted using PubMed, PMC, Google Scholar, Ovid and Cochrane Library databases. The search was proceeded using the keywords "gummetal orthodontic wire".

Material for in vitro study comprised five types of 0.016"x0.022" 10 cm long straight wires (n=50), including (ten specimens each): stainless steel (Remanium, Dentaurum), cobalt-chromium (Elgiloy Blue, RMO), nickel-titanium (Nickel Titanium, G&H), titanium-molybdenum (BetaForce, Ortho Technology), and Gummetal wires (Gummetal, JM Ortho Corporation), stainless steel brackets (Discovery, Dentaurum) with declared slot sizes of 0.018”x0.025” (0.018” slot) and Roth prescription for the maxillary right canine (n=50) and elastic ligatures (Alastik Easy-To-Tie, 3M) (n=50).

METHODS

Articles that included double-blind randomized clinical trials (RCTs), controlled clinical trials, in vitro studies, and had an abstract in English were included in the review. All papers that did not directly investigate the properties of Gummetal orthodontic wire, reviews, author discussions, abstracts, editorials, opinions, and case reports were rejected.

Prior to laboratory tests, each bracket was bonded to a steel plate. Then, each wire was ligated to the bracket with elastic ligature. Afterwards, each model was mounted in the base handle of the MultiTest 2.5-i testing machine (Mecmesin Ltd.) Subsequently, the wire was pulled through at a crosshead speed of 10 mm/min. The dynamic frictional force was measured by averaging the friction forces exerted during the 120 seconds long-lasting movement of the wire. The machine was recording 1000 measurements of friction force per second in dry state at room temperature. Recorded measurements were then saved on PC employing Emperor (Mecmesin Ltd.) force testing software. Each of the 50 tests performed comprised a new section of a wire, new bracket and new elastic ligature.

The surface topography of the orthodontic wires was examined by focus variation microscopy using a specialized optical system for 3D measurement Infinite Focus G5 plus (Bruker Alicona).

RESULTS:

Thirteen publications from Pubmed, Cochrane and Google Scholar databases were finally selected for critical review. Surprisingly, only one double-blind randomized clinical trial (RCT) was found in the literature. The remaining papers were in vitro studies.

Based on the critical literature review, Gummetal orthodontic wires present low bending strength, low fatigue limit, very low Young's modulus, and high elasticity. Gummetal generates higher forces than Supercable archwire, but lower than Nitinol and TMA. The coefficient of friction of Gummetal alloy is comparable to nickel-titanium and cobalt-chromium and, according to some authors, stainless steel.

In laboratory tests, it was found that stainless steel wires generated dynamic frictional forces with an average value of 0.639N, nickel-titanium 1.143N, cobalt-chromium 1.097N, titanium-molybdenum 1.932N, and Gummetal 1.198N. Topographical analysis of the archwire surfaces revealed that Gummetal wire did not significantly differ from the other alloys in fundamental aspects.

CONCLUSIONS

The literature review revealed that scientific information regarding Gummetal wire is very limited. Due to its non-toxic composition, Gummetal archwires might be used instead of nickel-titanium wires in the initial phase of orthodontic treatment in patients with nickel allergy. However, Gummetal wire provides a lower resistance to plastic deformation than nickel-titanium wires, which questions its superelasticity.

The Gummetal alloy orthodontic wires tested in the laboratory experiments of the present thesis showed dynamic friction values similar to nickel-titanium and cobalt-chromium wires, higher than stainless steel wires, and lower than titanium-molybdenum wires. The low coefficient of friction of Gummetal alloy seems suitable for sliding mechanics during orthodontic tooth movement in multibracket treatment. Topographical analysis of all five orthodontic wires confirmed, that the frictional force is not directly related to the surface, which will make wear tests in the future independent on topography.

More studies are necessary to assess the usefulness of Gummetal wire in clinical practice.

8. OMÓWIENIE PRAC WCHODZĄCYCH W SKŁAD OSIĄGNIĘCIA NAUKOWEGO

Wprowadzenie

Łuki ortodontyczne są stosowane w leczeniu wad zgryzu aparatami stałymi cienkołukowymi w celu uzyskania pożądanego ustawienia zębów w trakcie aktywnej fazy leczenia ortodontycznego. Siły przesuwające zęby powstają dzięki sprężystości drutów ortodontycznych. W epoce Angle'a i Tweeda (początek XX wieku) jedynie łuki ze stopu złota i niklu były wystarczająco odporne na korozję oraz na tyle sprężyste, aby można je było stosować w leczeniu ortodontycznym.

Druty ze stali nierdzewnej (SS) są powszechnie znane ze swojej sztywności oraz niskiego współczynnika tarcia w porównaniu z innymi drutami ortodontycznymi [1]. Zastosowanie kombinacji drutów i zamków wykonanych ze SS było przez lata złotym standardem dla ortodontów podczas leczenia z wykorzystaniem mechaniki ślizgowej. Łuki z SS są również uznawane za materiał referencyjny do oceny właściwości mechanicznych nowo wytwarzanych łuków ortodontycznych [2,3].

Drut chromokobaltowy (CoCr) pojawił się w latach 60. ubiegłego wieku [4]. Jedną z jego zalet jest niska twardość. Po wcześniejszym uformowaniu, drut CoCr może być utwardzony przez podgrzanie, co znacznie zwiększa jego wytrzymałość. Przez wiele lat stopy SS i CoCr były powszechnie stosowane w leczeniu ortodontycznym.

W latach 70. drut niklowo-tytanowy (NiTi) rozpoczął kolejną erę w ortodoncji. Jego superelastyczność i pamięć kształtu znacznie uprościły początkową fazę leczenia ortodontycznego. Jest on jednak również trudny do doginania, co czyni go nieodpowiednim do zastosowania podczas środkowej i końcowej fazy leczenia ortodontycznego [5]. Ponadto, stop NiTi zawiera około 50% niklu, który może prowokować organizm do wytwarzania przeciwciał w reakcji alergicznej [6].

Stopy beta-tytanu (β-Ti) są bardzo ważną grupą stopów bezniklowych i bezchromowych, które znalazły szerokie zastosowanie we współczesnej medycynie. Łatwiejsze do doginania niż NiTi, łuki tytanowo-molibdenowe (TiMo) wyprodukowano w latach 80. XX wieku. Łączą one w sobie wysoką wytrzymałość i sprężystość, co sprawia, że są odpowiednie do końcowej fazy leczenia ortodontycznego (szczególnie druty o przekroju prostokątnym). Łukom TiMo brakuje jednak sztywności i formowalności CoCr oraz nie nadają się do zadań wymagających bardzo dużej elastyczności drutu ortodontycznego [7]. Kolejną wadą drutów TiMo są siły tarcia o wysokich wartościach, które powstają pomiędzy zamkiem i łukiem ortodontycznym [8]. Postęp w produkcji nowych drutów β-Ti oraz innych stopów tytanu gwałtownie przyspieszył w ostatnim czasie, częściowo ze względu na ich wysoką biokompatybilność [7].

Poszukiwania idealnego drutu ortodontycznego trwają do dziś. Metale i stopy przeznaczone do zastosowań biomedycznych wymagają specyficznych właściwości, takich jak wyjątkowa biokompatybilność, brak toksyczności oraz wysoka odporność na korozję [9]. Doskonały łuk ortodontyczny powinien mieć estetyczny wygląd, być sprężysty, łatwy do formowania i zginania, a także charakteryzować się wysoką wytrzymałością na rozciąganie oraz pamięcią kształtu. Ponadto powinien zapewniać niski współczynnik tarcia, umożliwiając efektywne przesuwanie zębów przy zastosowaniu niskich (biologicznych) sił.

Gummetal jest nowatorskim, wielofunkcyjnym stopem β-Ti opracowanym w Japonii w 2001 roku w Sekcji Badań Metalurgicznych firmy Toyota Central R&D, Inc. Składa się z tytanu, niobu, tantalu, cyrkonu i tlenu. Skład chemiczny Gummetalu (Ti-23Nb-0.7Ta-2Zr-1.2O) został oparty na atomowej teorii walencyjnej [10]. Stop ten jest intensywnie obrabiany na zimno w celu uzyskania jego wyjątkowych właściwości. Cechy Gummetalu wynikają z zestawienia trzech magicznych liczb elektronowych: średniej kompozycyjnej liczby elektronów walencyjnych wynoszącej 4,24 elektronów walencyjnych na atom, rzędowości wiązań (BO) wynoszącej 2,87 oraz wartości Md wynoszącej 2,45 eV (elektronowo-orbitalny poziom energetyczny "d"). Według producentów, ten nietoksyczny stop łączy w sobie nie tylko wysoką wytrzymałość, ale również bardzo dużą sprężystość dzięki wyjątkowo niskiej wartości modułu Younga. Niezwykle rzadkie jest posiadanie przez stop metali obu tych właściwości jednocześnie. Dodatkowo w Gummetalu, jak podają producenci, odkształcenie plastyczne (ruch dyslokacyjny kryształu) jest całkowicie kontrolowane, co czyni go unikalnym [11].

Według Hasegawy [12], Gummetal wydaje się być niemal idealnym materiałem na łuk ortodontyczny. Zakłada się, że stop TiNbTaZrO może wytwarzać niewielkie siły już na wczesnym etapie leczenia stłoczeń. Ponieważ właściwości Gummetalu przeczą prawu Hooke'a (zależności odkształcenia od naprężenia), może on wytwarzać niskie biologiczne siły nawet przy dużych przemieszczeniach zębów.

Celem niniejszej pracy było zweryfikowanie i potwierdzenie reklamowanych właściwości tego nowego łuku ortodontycznego, takich jak: ekstremalnie niski moduł sprężystości, wysoka wytrzymałość na rozciąganie, wysoka sprężystość, biokompatybilność, pamięć kształtu, niski współczynnik tarcia, niska wytrzymałość na zginanie i niska granica zmęczenia.

Publikacja 1.

Właściwości kliniczne i fizyczne drutu ortodontycznego Gummetal w porównaniu z innymi łukami ortodontycznymi – przegląd krytyczny. Schmeidl, K.; Janiszewska-Olszowska, J.; Grocholewicz, K. Clinical Features and Physical Properties of Gummetal Orthodontic Wire in Comparison with Dissimilar Archwires: A Critical Review. *BioMed Res. Int.* **2021**, *2021*, 6611979.

Celem krytycznego przeglądu piśmiennictwa było znalezienie dowodów naukowych opisujących mechaniczne i kliniczne cechy łuków ortodontycznych z Gummetalu. Przegląd piśmiennictwa przeprowadzono w lutym 2020 roku z użyciem słów kluczowych: "gummetal orthodontic wire" w elektronicznych bazach danych: PubMed, PMC, Google Scholar, Ovid oraz Cochrane Library. Wyselekcjonowano prace badające bezpośrednio właściwości drutu ortodontycznego Gummetal.

Wszystkie wyszukane abstrakty 322 prac zostały przeczytane w celu wyłonienia badań kwalifikujących się do przeglądu. Następnie uzyskano pełne teksty prac. Nie stosowano ograniczeń dotyczących daty publikacji oraz języka, jeśli przynajmniej abstrakty artykułów lub streszczenia rozpraw doktorskich były w języku angielskim. Kryteria włączenia do przeglądu obejmowały (1) randomizowane podwójnie zaślepione badania kliniczne (RCT), (2) kontrolowane badania kliniczne oraz (3) badania in vitro. Odrzucono: (1) prace nie badające bezpośrednio właściwości drutu ortodontycznego Gummetal, (2) przeglądy piśmiennictwa, (3) dyskusje autorskie, (4) streszczenia, (5) artykuły redakcyjne, (6) opinie i (7) opisy przypadków. Następnie poddano analizie pełne teksty wszystkich wyselekcjonowanych prac.

Do przeglądu krytycznego ostatecznie zakwalifikowano trzynaście publikacji. Badania opisane w powyższych artykułach obejmowały następujące aspekty związane ze stosowaniem Gummetalu: mikrostruktura i właściwości mechaniczne [13], ocena zastosowania Gummetalu do wstępnego szeregowania zębów [14], badanie powstających sił [15], właściwości zginania [16], ocena zmęczenia materiału [17], współczynnik tarcia [18,19], moment obrotowy [20], powstające in vitro rozkłady naprężeń i odkształceń [21–24] oraz właściwości kalorymetryczne i termomechaniczne [25].

Wyniki tego przeglądu wskazują na duże zróżnicowanie analizowanych badań. W piśmiennictwie odnaleziono tylko jedną pracę opisującą badania kliniczne. W publikacjach prezentowano wyniki badań różnych właściwości Gummetalu uzyskanych różnymi metodami. Potwierdzono niską wytrzymałość Gummetalu na zginanie [16,17], niską granicę zmęczenia [17] oraz wysoką sprężystość [17]. Gummetal generuje mniejsze siły niż Nitinol i TMA, ale większe niż łuk pleciony Supercable [15]. Stwierdzone odkształcenie plastyczne Gummetalu w fazie szeregowania zębów kwestionuje jego superelastyczność oraz pamięć kształtu [15,16]. Współczynnik tarcia drutu Gummetal jest porównywalny do drutów CoCr i NiTi [18,19]. Ze względu na nietoksyczny skład chemiczny, Gummetal może być przydatny w początkowej fazie leczenia ortodontycznego u pacjentów z alergią na nikiel i/lub chrom [14]. Konieczne są dalsze badania w celu oceny przydatności Gummetalu w praktyce klinicznej.

Wnioski:

1. Łuk ortodontyczny z Gummetalu może być przydatny w początkowej fazie leczenia ortodontycznego alternatywnie do drutów NiTi. Wykazuje on jednak pewne odkształcenia plastyczne, co stawia pod znakiem zapytania jego superelastyczność.

2. Gummetal może być bezpiecznie stosowany u pacjentów z alergią na chrom i/lub nikiel; wszystkie pierwiastki atomowe tego stopu są nietoksyczne i biokompatybilne.

3. Drut z Gummetalu posiada niską wytrzymałość na zginanie, niską granicę zmęczenia i wysoką sprężystość. Wykazuje podobne ryzyko pęknięcia do innych drutów β-Ti (TMA, Resolve).

4. Utrata przyłożonej siły spowodowana tarciem drutu Gummetal jest porównywalna z drutami NiTi, CoCr, a także, wg niektórych autorów, SS.

5. Druty TiNbTaZrO mogą wykazywać odpowiedni moment obrotowy i niskie wartości naprężenia, gdy są stosowane w połączeniu z aparatami Edgewise w technice Gummetal Edgewise Archwire (GEAW).

6. Łuki ortodontyczne z Gummetalu wykazują bardzo niską wartość modułu Younga, stałą przy zmianach temperatury przy jednocześnie wysokiej wytrzymałości na rozciąganie. Te cechy zapewniają generowanie mniejszych sił od Nitinolu i TMA, ale większych od łuku Supercable.

Publikacja 2.

Badanie tarcia nowego drutu ortodontycznego ze stopu TiNbTaZrO – porównanie in vitro z innymi łukami ortodontycznymi. Schmeidl, K.; Wieczorowski, M.; Grocholewicz, K.; Mendak, M.; Janiszewska-Olszowska, J. Frictional Properties of the TiNbTaZrO Orthodontic Wire—A Laboratory Comparison to Popular Archwires. *Materials* **2021**, *14*, 6233.

Tarcie jest siłą, która przeciwstawia się ruchowi dowolnych powierzchni stykających się ze sobą [26]. Siła tarcia w ortodoncji występuje w wielu punktach kontaktu na granicy zamek - łuk ortodontyczny podczas leczenia wad zgryzu aparatami stałymi cienkołukowymi. Zamki przyklejone do różnych powierzchni zębów przy pomocy łuków ortodontycznych przenoszą na nie siły [27]. Na ruch zębów wpływa tarcie statyczne i dynamiczne [28]. Przesuwanie zębów w jamie ustnej podczas leczenia ortodontycznego odbywa się z niewielką prędkością. Czynnikami mającymi wpływ na tarcie występujące pomiędzy elementami aparatów stałych cienkołukowych są: rodzaj drutu ortodontycznego, rodzaj zamka, sposób ligaturowania oraz czynniki biologiczne [29,30].

Do produkcji drutów ortodontycznych stosowanych w aktywnej fazie leczenia ortodontycznego wykorzystuje się różne stopy. Praktykujący lekarze powinni znać współczynniki tarcia cechujące poszczególne łuki ortodontyczne, szczególnie te stosowane podczas przesuwania zębów *en masse* oraz retrakcji kłów. Stosując mechanikę ślizgową, generuje się pomiędzy drutem, zamkiem i ligaturą siły tarcia, które utrudniają ruch zęba w fazie retrakcji i przenoszą jednocześnie siły na zęby boczne. Siły te wpływają negatywnie na wymagane zakotwienie oraz mogą prowadzić do utraty zakotwienia [31]. W związku z powyższym, idealny drut ortodontyczny powinien charakteryzować się niskim współczynnikiem tarcia, umożliwiając tym samym efektywne i swobodne przemieszczanie zębów.

We wcześniejszych badaniach tarcia drutów ortodontycznych w zamkach metalowych najwyższe wartości tarcia generowały druty TiMo, natomiast niższe siły generowały kolejno druty NiTi i SS [32]. W innych badaniach również stwierdzono, że najmniejsze tarcie wytwarzały druty SS , natomiast wyższe - kolejno druty CoCr, NiTi i TiMo [33].

Przeglądając piśmiennictwo, znaleziono jedynie jeden recenzowany artykuł porównujący siły tarcia drutów ortodontycznych ze stopu TiNbTaZrO, NiTi oraz TiMo [18]. Nie odnaleziono żadnych opublikowanych badań porównujących tarcie Gummetalu z innymi konwencjonalnie stosowanymi drutami niebędącymi stopami tytanu.

Celem niniejszej pracy było określenie kinetycznych sił tarcia drutu Gummetal oraz porównanie ich z wartościami siły tarcia innych lepiej poznanych stopów stosowanych w produkcji łuków ortodontycznych. Ponadto, autorzy postanowili porównać topografię powierzchni drutu z Gummetalu ze stopami SS, CoCr, NiTi oraz TiMo, z użyciem metody mikroskopii różnicowania ogniskowego.

W badaniach tarcia wykorzystano 50 zamków SS (Discovery, Dentaurum) o deklarowanych rozmiarach slotu 0,018"x0,025" (slot 0,018") i preskrypcji wg Rotha dla prawego kła górnego. Zbadano pięć rodzajów drutów prostych o przekroju 0,016"x0,022" i długości 10 cm (n=50), w tym (po dziesięć egzemplarzy): druty SS (Remanium, Dentaurum), CoCr (Elgiloy Blue, RMO), NiTi (Nickel Titanium, G&H), TiMo (BetaForce, Ortho Technology) oraz druty TiNbTaZrO (Gummetal, JM Ortho Corporation), które przymocowano do zamków za pomocą ligatur elastycznych (Alastik Easy-To-Tie, 3M).

Każdy z zamków został przyklejony do stalowej płyty S235JR o grubości 1,4 mm, szerokości 50 mm i długości 115 mm za pomocą kleju cyjanoakrylowego (Kemsin KC-1200, Chemkon). Wszystkie procedury klejenia zamków, w celu standaryzacji, wykonał jeden operator. Badania przeprowadzono w temperaturze pokojowej. Każdy z drutów został przymocowany do zamka za pomocą ligatury elastycznej tak, aby dolny, krótszy koniec drutu, pozostał wolny.

Następnie każdy model zamocowano w uchwycie przy podstawie urządzenia MultiTest 2.5-i (Mecmesin Ltd.) z dużą dokładnością. Płytkę stalową umieszczono w uchwycie maszyny, a następnie zamocowano ją w taki sposób, aby prosty drut był ustawiony prostopadle do podstawy maszyny oraz jednocześnie równolegle do szczeliny zamka.

Następnie odcinek 10 mm górnego końca drutu mocowano w specjalnej głowicy maszyny z czujnikiem siły do 10 N i dokładnością ±0,1%. Każdy drut przesuwano z prędkością 10 mm/min na odcinku 20 mm; w tym czasie maszyna rejestrowała 1000 pomiarów siły tarcia na sekundę. Tarcie kinetyczne mierzono poprzez uśrednienie wartości sił tarcia powstających podczas 120-sekundowego ruchu drutu względem zamka. Zarejestrowane pomiary dynamicznych sił tarcia dla każdej z 50 kombinacji drut-ligatura-zamek zostały zapisane w komputerze ze specjalistycznym oprogramowaniem Emperor (Mecmesin Ltd.) do rejestrowania badanych sił.

Analizę statystyczną przeprowadzono przy użyciu programów IDE w wersji 1.4.1106 (RStudio) oraz R w wersji 4.0.4 (R Core Team). Do wstępnego oszacowania wielkości próby autorzy wykorzystali obliczenia mocy dla ogólnych modeli liniowych. Przyjmując stopnie swobody dla u = 4 (dla 5 grup), wielkość efektu f2 = 0,4 (użyto średniej wartości dla testowania priorytetowego), poziom istotności 5% oraz wysoką wartość mocy = 0,75, całkowita liczba próbek w niniejszym eksperymencie powinna wynosić co najmniej 48, a więc liczba 50 próbek (10 prób na grupę) spełniała powyższe warunki [34,35].

Siedem z dziesięciu porównywanych par grup wykazało różnice istotne statystycznie. Średnie dla grup Remanium i BetaForce różniły się istotne statystycznie zarówno między sobą, jak i między wszystkimi pozostałymi grupami. Nie stwierdzono, natomiast istotnych statystycznie różnic pomiędzy porównywanymi średnimi wartościami sił dla par NiTi-Gummetal, Gummetal-CoCr oraz NiTi-CoCr. Spośród badanych prób, najniższe wartości tarcia kinetycznego wykazał drut Remanium, najwyższe - BetaForce, średnie siły wykazały natomiast CoCr, NiTi i Gummetal.

Do badań topografii powierzchni drutów ortodontycznych wykorzystano specjalistyczne urządzenie do pomiarów optycznych 3D Infinite Focus G5 plus (Bruker Alicona). Stwierdzono, że druty stalowe generowały siłę tarcia kinetycznego o średniej wartości 0.639N, niklowotytanowe 1.143N, chromokobaltowe 1.097N, tytanowomolibdenowe 1.932N, natomiast druty z Gummetalu 1.198N.

Analiza topograficzna wykazała, że powierzchnia łuku z Gummetalu zasadniczo nie różniła się od powierzchni pozostałych stopów.

Wnioski:

1. Druty ze stopu Gummetal generują tarcie podobne jak druty CoCr i NiTi. Wartości sił tarcia wytwarzanego przez stop Gummetal są niższe od tarcia drutów TiMo, natomiast wyższe od drutu ze stopu SS.

2. Powierzchnia łuku z Gummetalu nie różni się istotnie od powierzchni innych badanych łuków.

Podsumowanie

Stopy β-Ti mają istotne i szerokie zastosowanie w technologii i medycynie, m.in. w lotnictwie, budowie silników oraz produkcji implantów ortopedycznych i ortodontycznych, dzięki swoim wyjątkowym właściwościom i łatwości wytwarzania [36].

Poszukiwania idealnego drutu ortodontycznego z pewnością nie dobiegły końca [40]. Stosowanie materiałów ortodontycznych jest zawsze obarczone niebezpieczeństwem wystąpienia niepożądanych reakcji alergicznych wynikających z korozji, korozji galwanicznej i uwalniania jonów metali z różnych stopów [37]. Gummetal charakteryzuje typowa dla stopów β-Ti doskonała odporność na korozję, nietoksyczność i biokompatybilność dzięki składowi chemicznemu pozbawionemu niklu i chromu [10,36].

Dla bezpiecznego przemieszczania zębów podczas leczenia wad zgryzu pożądane i optymalne są niewielkie siły biologiczne [38]. Wydaje się, że dzięki cechom takim jak: łatwość wykonywania dogięć, odpowiedni moment obrotowy, generowanie niskich sił, wysoka sprężystość i odporność na rozciąganie, druty z Gummetalu mogą zastąpić łuki NiTi, SS, CoCr i TiMo w wybranych sytuacjach klinicznych na różnych etapach leczenia ortodontycznego, a szczególnie: w fazie końcowej – do wykonywania dogięć oraz w fazie początkowej – u pacjentów z alergią na nikiel [25]. Drut z Gummetalu może być także z korzyścią stosowany wtedy, gdy łuk leczniczy dogina się od początku leczenia ortodontycznego. Należy jednak podkreślić, że drut z Gummetalu jest podatny na odkształcenia plastyczne. Nie jest zatem łukiem leczniczym z wyboru w początkowych etapach leczenia, gdy zęby nie są jeszcze uszeregowane; u pacjentów bez alergii na nikiel korzystniejsze wydaje się tu stosowanie mniej wrażliwych na trwałe odkształcenia i tańszych łuków NiTi [15].

Istotne wyzwanie kliniczne stanowi w leczeniu ortodontycznym aparatami stałymi cienkołukowymi tarcie. Zastosowanie materiałów zapewniających niższe wartości sił tarcia zmniejsza utratę sił generowanych podczas przesuwania zębów wzdłuż łuku ortodontycznego oraz ogranicza utratę zakotwienia [39]. W badaniach własnych wykazano, że wartości sił tarcia wytwarzanego przez stop Gummetal są niższe od tarcia drutów TiMo, natomiast wyższe od drutu ze stopu SS. Wyniki te są spójne z uzyskanymi w pracy Takady i wsp. [18], którzy stwierdzili, że TiMo wykazuje statystycznie wyższe wartości tarcia niż Gummetal, a łuki NiTi wykazują porównywalne tarcie do stopu TiNbTaZrO. Badania własne wykazały także, że wielkość siły tarcia nie zależy bezpośrednio od właściwości powierzchni badanego łuku ortodontycznego.

Na koniec należałoby dodać, że właściwości stopów różnią się zależnie od ich składu, ale także sposobu obróbki. Istnieją także inne stopy TiMo i TiNbTaZrO, pochodzące od różnych producentów, posiadające różne właściwości mechaniczne [16]. Jeśli stopy tego typu zyskają większą popularność i znajdą szersze zastosowanie w ortodoncji, zasadne będzie badanie specyficznych właściwości poszczególnych stopów β-Ti, co umożliwi ich optymalne stosowanie w praktyce klinicznej. Istnieje wiele różnych metod i testów, które można przeprowadzić w celu porównania właściwości nowych i starszych drutów ortodontycznych [41–45].

Zaskakujące jest, że od 2003 roku, kiedy pojawiły się pierwsze doniesienia na temat ogromnego potencjału stopu Gummetal, do chwili obecnej, w dostępnym piśmiennictwie istnieje tylko jedno randomizowane podwójnie zaślepione badanie porównujące efekty leczenia ortodontycznego Gummetalem z NiTi [14]. Dalsze kierunki badań nad stopem Gummetal powinny zatem obejmować randomizowane podwójnie zaślepione badania kliniczne oraz analizy laboratoryjne, między innymi: potencjodynamiczne, podatności na korozję, sztywności, elastyczności, sprężystości, plastyczności, testy wytrzymałościowe i zużycia, porównujące różne właściwości Gummetalu z innymi materiałami w celu określenia optymalnego zastosowania tego stopu w leczeniu ortodontycznym.

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Hindawi
BioMed Research International
Volume 2021, Article ID 6611979, 9 pages
https://doi.org/10.1155/2021/6611979

Review Article

Clinical Features and Physical Properties of Gummetal Orthodontic Wire in Comparison with Dissimilar Archwires: A Critical Review

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Received 14 October 2020; Revised 24 December 2020; Accepted 15 January 2021; Published 28 January 2021

Academic Editor: Vincenzo Grassia

Objective. Gummetal is a novel multifunctional alloy which possesses distinctive properties with the potential to refine and amend the efficacy of orthodontic treatment. The objective of this critical literature review was to investigate scientific evidence concerning the mechanical and clinical features of this recently manufactured beta-titanium orthodontic wire. *Materials and Methods*. Electronic databases: PubMed, PMC, Google Scholar, Ovid, and Cochrane Library were searched. Studies investigating the properties of Gummetal orthodontic wire including in vitro and clinical studies were selected, validity was assessed, and data was extracted. The risk of bias was assessed by the Cochrane risk of bias Tool 2.0 in a randomized clinical trial. *Results and Discussion*. Among 322 papers, 13 papers were selected and divided into two groups: prospective double-blinded randomized clinical trial and in vitro studies. *Conclusions*. The results of this review should be interpreted with caution because of the heterogeneity of the studies. Only single clinical trial paper was found in the literature. The studies reported different characteristics obtained by various methods; thus, it was difficult to objectively compare the results. Low bending strength, low fatigue limit, and high resilience have been confirmed. Gummetal provides lower force than Nitinol and TMA but higher than Supercable wire. Plastic deformation of Gummetal questions its superelasticity. Friction of Gummetal wire is comparable to SS and CoCr wires. Because of its nontoxic chemical composition, Gummetal might be useful in the initial phase of orthodontic treatment for patients suffering from nickel allergy. Further studies are necessary to assess the usefulness of Gummetal in the clinical practice.

1. Background

Orthodontists use archwires in multibracket appliances in order to achieve a 3D control of tooth movement in the active phase of orthodontic treatment. The force moving the teeth is provided by the elasticity of orthodontic wire. In the Angle and Tweed era, only gold-nickel alloy wire resisted corrosion and was elastic enough to make it available for orthodontic treatment. In 1933, in the United States, Rocky Mountain Orthodontics started producing cobalt-chromium (CoCr) (Elgiloy). It had similar strength and Young Modulus as gold-nickel wire but was much cheaper and quickly became the material of choice. For years, CoCr and stainless steel (SS) wires have been a standard in orthodontic treatment [1].

In the 1970s, nickel-titanium (NiTi) wire started the next era in orthodontics. Its superelasticity and shape memory simplified the initial phase of orthodontic treatment. However, it is also almost impossible to bend which makes it inadequate for the middle and final phases of orthodontic treatment [2]. In addition, NiTi alloy contains 50% of nickel, which may provoke the body to produce antibodies in allergic reaction [3]. Elimination of heavy metals from orthodontic wires was desired.

Beta-titanium (β-Ti) alloys are the next and a very important class of nickel and chromium-free alloys that have found use in demanding medical applications such as orthodontic and orthopedic implants and orthodontic wires. For orthodontic use, bendable titanium-molybdenum (TiMo) wires were fabricated with similar properties to CoCr and NiTi alloys [4]. β-Ti wires are suitable to replace CoCr and SS wires, but, unfortunately, they are not good for applications in which NiTi alloys flexibility is required.

The search for an ideal orthodontic wire has not come to an end yet. Metals and alloys designed for biomedical applications require specific properties, such as an exceptional biocompatibility, lack of toxicity, and good corrosion resistance [5]. The perfect orthodontic archwire should be aesthetic, very elastic, formable, and easy to bend with high tensile strength as well. Moreover, it should provide low coefficient of friction moving the teeth efficiently and be able to control the orthodontic force freely.

Gummetal is a novel multifunctional β-Ti alloy developed in Japan in 2001 at the Metallurgy Research Section of Toyota Central R&D, Inc. It consists of titanium, niobium, tantalum, zirconium, and oxygen. Gummetal's chemical composition (Ti-23Nb-0.7Ta-2Zr-1.2O) was based on its atomic valence theory [6]. This alloy is intensively cold-worked to produce its important characteristics. Gummetal properties arise from the juxtaposition of three electronic magical numbers: a compositional average valence electron number of 4.24 valence electrons per atom, bond order (BO-value) of 2.87, and Md value of 2.45 eV ("d" electron-orbital energy level). According to the producers, this nontoxic alloy combines not only high strength but also very high elasticity due to the extremely low value of Young's modulus, which is exceptionally rare for a metal alloy to possess both of these properties at the same time. In this novel alloy, as stated by the manufacturers, plastic deformation (the dislocation motion of the crystal) is controlled completely which makes it unique [7].

As claimed by Hasegawa [8], Gummetal appears to be almost ideal material for orthodontic archwire. It is assumed to produce a small continuous force from an early stage of crowding treatment. Because Gummetal does not follow Hooke's law, it could lessen the orthodontic force even with large teeth displacement.

The aim of the present study was to verify and confirm the advertised properties of this novel β-Ti archwire as extremely low elastic modulus, super high tensile strength, high flexibility, nontoxicity, dislocation-free plastic deformation mechanism, low coefficient of friction, low bending strength, and low fatigue limit.

2. Materials and Methods

Literature search was proceeded in February 2020 using the keywords: "gummetal orthodontic wire" in the following databases:

(i) PubMed

(ii) PMC

(iii) Google Scholar

(iv) Ovid

(v) Cochrane Library

The PRISMA flow diagram is presented in Figure 1.

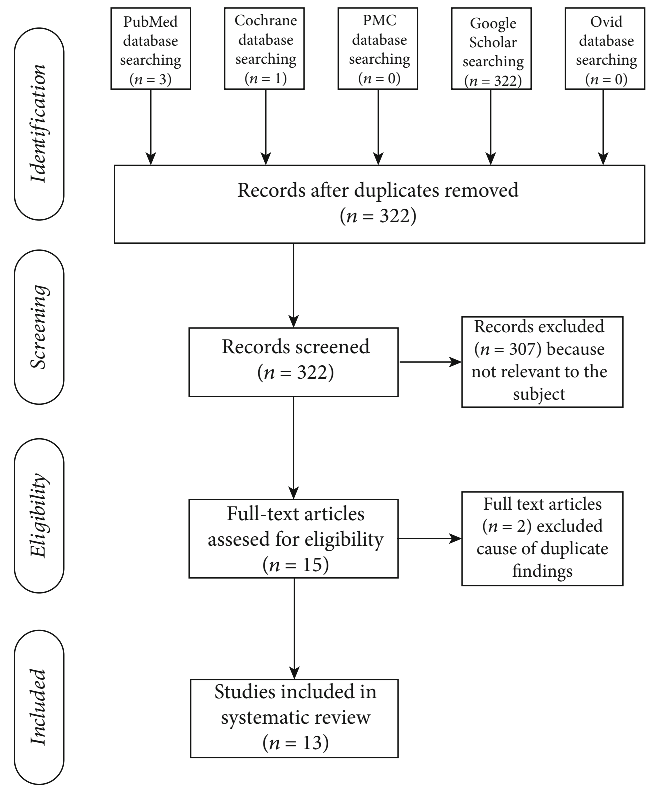

Figure 1: PRISMA flow diagram.

All titles and abstracts were read by the first and verified by the second author to retrieve eligible studies. Then, full texts of papers included were obtained. No date or language limits were applied if at least article's abstracts were in English. The inclusion criteria comprised (1) double-blinded randomized clinical trials (RCT), (2) controlled clinical trials, and (3) in vitro studies. The exclusion criteria were (1) papers not investigating directly the properties of Gummetal orthodontic wire, (2) reviews, (3) authors' debates, (4) abstracts, (5) editorials, (6) opinions, and (7) case reports. All full texts of papers included were retrieved and analyzed. Hand search was proceeded in reference lists of the studies included. The authors used Cochrane risk of bias (RoB) Tool 2.0 to assess the RoB of the selected RCT [9].

3. Results

Initially, fifteen papers proved eligible for a critical review. However, two of them had to be excluded because of the duplication of the findings described. Two studies (one article and one dissertation) covered the same double-blind RCT and were cowritten by the same first author. Another group of authors published the same findings twice: in Japanese (2013) and in English (2015). Surprisingly, there was only one RCT paper found in the literature (Table 1).

All the latter were in vitro studies (Table 2).

In included RCT study, the authors had some concerns regarding the bias due to deviations from intended intervention. The clinicians were aware of participants' assigned group during the trial. However, the patients were not most

Table 1: In vivo study.

Authors, year (language)	Study group	Outcome measured	Comparison	Main findings
Nordstrom et al. [10], 2018 (English)	28 patients; age: 12-20	Crowding reduction during initial orthodontic alignment in adolescents over time of 2 months	Fourteen 0.016″ NiTi archwires and fourteen 0.016″ Gummetal (experimental)	Both wires reduced Little's Irregularity Index (no significant difference between the wires tested), statistically insignificant increase in the transverse dimensions

likely conscious of archwire used and that presumably have not affected the outcome of the intervention. Two domains were judged to present high RoB. The overall RoB of this study was evaluated high which corresponds to the worst risk of bias in any of the domains (Figure 2) [9].

3.1. Microstructure and Mechanical Properties. The microstructure and mechanical properties of cold-drawn and annealed TNTZO (Ti-Nb-Ta-Zr-O, Gummetal) wires (prepared by powder metallurgy) with 0.3 mm diameter were analyzed by Zhang et al. [11]. The microstructure of cold drawn TNTZO consisted of nanometer-sized elongated drains "marble-like" in cross-section with 70 nm width. After 700°C 5 min annealing, the grain size increased to approximately 5 μm. The cold-drawn wires exhibited better mechanical properties, higher tensile strength (around 1000 MPa) and similar Young's Modulus (69 MPa) compared to annealed wires. In addition, TNTZO wire presented higher creep resistance and lower stress exponent compared to titanium (Ti) and TC4 wires of the same diameter.

3.2. Initial Teeth Alignment and Force System Evaluation. The clinical efficiency of 0.016″ Gummetal and 0.016″ NiTi orthodontic wires during teeth alignment in the first two months of treatment was compared by Nordstrom et al. [10] in a prospective, double-blind randomized clinical trial. Twenty-eight patients were divided into two equal groups. During the treatment, digital scans were performed and then used to assess changes in Little's Irregularity Index and the alteration in intercanine and intermolar widths. With Gummetal wire, there was 27% crowding reduction during the first month, and an additional 25% decrease in crowding was observed in the following month. There was no significant difference observed in the decrease in irregularity between the two groups over time. Moreover, there was no significant difference between the groups concerning the changes in intercanine and intermolar width.

The investigation of the initial force systems of Gummetal and its comparison to the Supercable, Nitinol and TMA archwires proved that Gummetal provided slightly lower (10% lower) force systems than Nitinol and higher than Supercable, which was the only archwire that has not exceeded the recommended values [12]. TMA delivered the highest force value. Moreover, the author noticed a plastic deformation after removing the archwires from the brackets in 7% of Nitinol wires, 60% of Gummetal wires, and 83% of TMA wires.

3.3. Bending Properties, Fatigue Evaluation. Thirteen different 0.016″ × 0.022″ β-Ti archwires (including Gummetal), SS, and NiTi wires were tested by Suzuki et al. [13] for stiffness, active deflection range, load at 3 mm displacement, and apparent plastic deformation. Among the wires tested, Gummetal presented the lowest stiffness (below 3 N/mm), second highest active deflection range after NiTi (approximately 1.75 mm), second lowest load at 3 mm deflection after NiTi (approximately 6 N), and apparent plastic deformation.

High-cycle fatigue behavior in three β-Ti wires (TMA 0.016″ × 0.022″, Resolve 0.016″ × 0.022″ and Gummetal 0.017″ × 0.022″) was analyzed by Murakami et al. [14] using static bending test and bending fatigue test. Among all wires studied, Gummetal exhibited the lowest elastic modulus, fatigue limit, and bending strength. It also performed the highest resilience. However, there was no difference observed in the number of cycles to failure among these three archwires. TMA, Gummetal, and Resolve presented similar risk of the archwire fracture.

3.4. Frictional Force (FF). The frictional forces (FFs) of titanium-niobium (TiNb, Gummetal), NiTi, and TiMo archwires in sizes 0.016″, 0.016″ × 0.022″, and 0.017″ × 0.025″ (in 0.018″-slot bracket) and 0.018″, 0.017″ × 0.025″, and 0.019″ × 0.025″ (in 0.022″-slot bracket) ligated with elastic modules at three different wire-bracket angles were compared by Takada et al. [15]. It has been revealed that the FFs increased gradually with the angle and size of the wire in both types of brackets. Moreover, Gummetal and NiTi archwires exerted comparable FFs, and those of TiMo presented the greatest FFs. In this study, all three alloys generated greater FFs in the 0.018″-slot bracket than in the 0.022″-slot bracket. Scanning microscope images revealed that the surface of TiMo was much rougher with abundant scratches visible than that of the NiTi and TiNb wires.

The amount of dynamic friction in dry state at room temperature was measured by Kopsahilis [16] in 660 in vitro tests with 132 different wire-bracket combinations. The loss of applied force due to friction of Gummetal was comparable to well-known archwires as CoCr and SS. No influence of the slot size on friction using different dimensions of Gummetal was found in nine out of twelve results.

3.5. Torque Moment. The torque moment provided by Gummetal wire was measured and compared with NiTi and TiMo archwires by Kuroda et al. [17]. Two sizes of TiNb, NiTi, and TiMb and 0.022″-slot SS brackets were ligated with elastic modules and ligature wires. The torque moment delivered by the bracket-wire combination was measured by means of a torque gauge at the temperature of 37°C and 50% humidity. The study revealed an increase of the torque moment

Table 2: In vitro studies.

No	Authors, year (lang.)	Wire type	Size of the wire	Outcome measured	Applied test	Main findings
	Zhang et al. [11], 2019 (English)	Gummetal Ti TC4	0.3 mm	Microstructural and mechanical properties of cold-drawn and annealed TNTZO wires	Optical Microscope and Transmission Electron Microscope (TEM, JEM 2100) used to characterize microstructure. Nanoindentation (UNHT) performed to test elastic modulus and creep behavior	Marble-like cross-section microstructure of cold-drawn TNTZO wire. The tensile strength of cold-drawn TNTZO (1000 MPa) much higher than annealed TNTZO (680 MPa) Similar elastic modulus: cold-drawn 69 GPa, annealed 65 GPa. TNTZO exhibited higher creep resistance and lower stress exponent than Ti and TC4 wires
	Grauberger [12], 2018 (German)	Gummetal Supercable TMA Nitinol Discovery SS brackets 0.018″	0.014″ (Gummetal) 0.016″ (Supercable) 0,016″ (TMA) 0.014 (Nitinol)	Initial force systems investigation of Gummetal and conventional wires	Initial 3D force systems were measured with 3D force moment sensor and RX 60 robot	Amount of force: Supercable $<$ Gummetal $<$ NiTinol $<$ TMA 60% of Gummetal wires showed plastic deformation The forces of NiTi, Gummetal and TMA exceeded the recommended values for leveling
	Suzuki et al. [13], 2015 (Japanese)	Beta-titanium (TiMo), CBA (TiMo), Beta III (TiMo), TitanMoly (TiMo), TMA (TiMo), LOW FRICTION TMA (TiMo), BT3 (TiMo), BENDALOY (TiMo), BETA TITANIUM (TiMo), β III (TiMo), Gummetal (Ti-Nb-Ta-Zr-O), TIMOLIUM (Ti-A-V), SS, NEO SENTALLOY F160 (NiTi)	0.016″ × 0.022″	Bending properties: stiffness, active deflection range, load at 3 mm displacement, plastic deformation	3-point bending test	Gummetal presented: lowest stiffness (below 3 N/mm) second highest active deflection range after NiTi second lowest load at 3 mm deflection (N) after NiTi apparent plastic deformation (only NiTi provided no plastic deformation)
	Murakami et al. [14], 2015 (English)	Gummetal Resolve TMA	0.017″ × 0.022″ (Gummetal) 0.016″ × 0.022″ (Resolve) 0.016″ × 0.022″ (TMA)	Fatigue evaluation, high-cycle fatigue test	Static 3 point bending test with 3 point bending mode SEM observation of fractured wires, micro X-ray diffraction of postfatigue crystal structures	Gummetal exhibited the lowest elastic modulus (44.54 MPa), bending strength (1.241 MPa), fatigue limit (304 MPa) and the highest resilience (0.00086 J).
	Takada et al. [15], 2018 (English)	TiNi, TiNb, TiMo, SS brackets 0.018″ and 0.022″, elastic modules	0.016″ 0.016″ × 0.022″ 0.017″ × 0.025″ (0.018″-slot-bracket 0.018″	Torque moment delivered by bracket-wire combinations	Dynamic FF at three bracket-wire angles (0°, 5°, 10°) with InStron 5567 loading apparatus	TiNb had almost the same dynamic FFs as the NiTi in 0.018″ bracket. TiMo presented significantly higher ($P < 0.05$) values. FFs were 1.5-2 times lower in 0.022″ bracket regardless of alloy wire type. SEM images showed that the surface of TiMo was much rougher with

Table 2: Continued.

No	Authors, year (lang.)	Wire type	Size of the wire	Outcome measured	Applied test	Main findings
			$0.017'' \times 0.025''$ $0.019'' \times 0.025''$ ($0.022''$-slot-bracket			scratches visible comparing to the other wires
	Kopsahilis [16], 2018 (German)	Gummetal SS Elgiloy NiTi TMA in various brackets: Clarity, Discovery, Inspire Ice, Micro Sprint brackets $0.018''$ and $0.022''$, steel wire ligation	$0.014''$ $0.016''$ $0.016'' \times 0.022''$ $0.019'' \times 0.025''$	Dynamic friction in the binding modus, dry state, room temperature	Robotic measurement system (RMS) test	Loss of applied force due to friction in Gummetal was comparable to SS and Elgiloy. Friction of Gummetal in Micro Sprint brackets was outstandingly low. Round wires provided lower friction (except for ceramic bracket Inspire Ice) Micro Sprint—low friction
	Kuroda et al. [17], 2014 (English)	TiNb NiTi TiMo, $0.022''$ SS brackets, elastic modules or ligature wires	$0.017'' \times 0.025''$ $0.019'' \times 0.025''$	Torque moment delivered by bracket-wire combinations	Measuring apparatus consisted of torque transducer connected to a torque gauge	TiNb presented unique torque characteristics - effective torque was smaller than those of TiMo and NiTi when applied torque was larger than 20°
	Meros et al. [18], 2019 (English)	Gummetal Blue Elgiloy Brackets $0018'' \times 0.025''$	$0.018'' \times 0.022''$ (Gummetal) $0.016'' \times 0.022''$ (Blue Elgiloy)	Tension distribution in the anterior region of mandible in MEAW and GEAW technique with and without intermaxillary elastics	Tension distribution assessed on photoelastic models simulating lower arch, measured by means of reflection polariscope	Gummetal with elastics generated the lowest mean tension values significantly different ($P < 0.05$) from the other groups MEAW with elastics and GEAW without elastic yielded tension values statistically similar ($P > 0.05$)
	Jácome et al. [19], 2016 (Spanish)	Blue Elgiloy (with multiloops) Gummetal Brackets SS $0.018''$	Blue Elgiloy $0.016'' \times 0.022''$ Gummetal $0.018'' \times 0.022''$	Distribution of stress and strain with and without intermaxillary elastics	Mandibular dentoalveolar unit generated by rapid programming and subjected to 300 g force applied by class III elastics (in specialized software)	Gummetal presented lower values of the strains than Blue Elgiloy. The use of elastics did not affect the distribution of stress and strain regardless tested alloy
	Pacheco et al. [20], 2014 (Spanish)	Gummetal Nitinol Buccal tube $0.018'' \times 0.025''$	$0.018'' \times 0.022''$	Distribution of stress and strain of the wires	Simulation of Newton 0.9807 mechanical load applied by mechanical stress in the pipe arch and distributed along the lower left quadrant on simulated observation unit	Gummetal showed less stress and deformation than NiTi under the same mechanical conditions
	Bertl et al. [21], 2013 (German)	Gummetal TMA Blue Elgiloy (with multiloops) Damon CuNiTi Sentalloy Green Sentalloy Black	$0.018'' \times 0.022''$ (Gummetal) $0.016'' \times 0.022''$ (Blue Elgiloy) Damon CuNiTi ($0.014'' \times 0.025''$	Uprighting moments produced with different archwires	2D measuring machine with three independent force tranducers for displaying horizontal (x-axis) and vertical (y-axis) forces, as well as moments around z-axis	No significant differences between Gummetal and TMA in producing uprighting moments were observed

Table 2: Continued.

No	Authors, year (lang.)	Wire type	Size of the wire	Outcome measured	Applied test	Main findings
		Sentalloy White Standard Edgewise 0.018″ brackets	and 0.016″ × 0.025″) Sentalloy Green (0.016″ × 0.022″) Sentalloy Black and White (0.017″ × 0.025″)			
	Laino et al. [22], 2012 (English)	Gummetal TMA 35° Copper NiTi Thermalloy Plus Nitinol SE NiTi	0.016″ (Gummetal) 0.016″ × 0.022″ (other alloys)	Mechanical and calorimetric properties of the wires	3-point bending test, dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC)	Gummetal and TMA presented flexural elastic modulus constant with temperature. TMA elastic modulus (105 GPa) was approximately twice higher than Gummetal's elastic modulus (40 GPa)

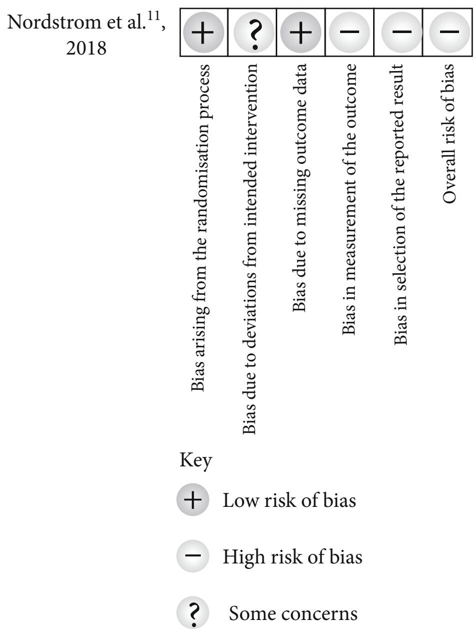

Figure 2: Cochrane risk of bias tool 2.0 results.

with increasing torque applied and wire size. The torque moment with elastic ligatures was significantly smaller than that with wire ligatures. With more than 20° torque applied, the torque moment of NiTi and TiMo wires was larger than that of Gummetal wire.

3.6. Distribution of Stress and Strain. The evaluation of tension distribution in two different orthodontic mechanical approaches to treat anterior open bite was the aim of the study of Meros et al. [18]. In the in vitro experimental study, the mandibular anterior teeth underwent orthodontic forces provided by Blue Elgiloy $0.016'' \times 0.022''$ in multiloop edgewise archwire (MEAW) and Gummetal $0.018'' \times 0.022''$ in Gummetal edgewise archwire (GEAW) techniques with and without anterior elastic bands placed between upper lateral incisors and lower canines. The GEAW technique with intermaxillary elastics generated the lowest mean tension values significantly different ($P < 0.05$) from the other groups. GEAW provided lower and more favorable tension levels than MEAW technique with Blue Elgiloy.

The distribution of stresses and deformations in the wire, the bracket, and the dentoalveolar unit with and without class III intermaxillary elastics applied, using Blue Elgiloy archwire with multiloops and Gummetal archwire by finite element analysis, was compared by Jácome et al. [19]. The distributed tension maintained its maximum values at the level of the crest, decreasing towards the mandibular symphysis and towards distal parts of the mandible; trend was shown when using both archwires. The stress and strain distributions for Gummetal and Blue Elgiloy wires were consistent with the distal "en bloc" movement in the teeth and cortical bone. The Blue Elgiloy with multiloops showed higher stress values compared to the Gummetal, when no elastic load was used.

The distribution of stress and strain in the dentoalveolar unit of lower left second molar with 20° inclination with alveolar bone, the wire and the tube with Gummetal and Nitinol by finite element analysis was compared by Pacheco et al. [20]. Gummetal archwire generated less effort (214.28 MPa) than Nitinol (219.93 MPa) and presented slightly smaller (0.007 mm) deformation. The molar, alveolar bone, and molar tube expressed greater stress and strain when using the Nitinol archwire compared to the Gummetal. In conclusion, under the same mechanical conditions, Gummetal showed less effort and deformation than Nitinol.

The comparison of Gummetal to conventional leveling-archwires for the "en bloc" uprighting of mesially inclined premolars and first molar was performed by Bertl et al. [21]. The clinical situation was simulated in a 2D measuring apparatus. Gummetal $0.018'' \times 0.022''$ and TMA $0.016'' \times 0.022''$ archwires produced similar and highest uprighting moments at the second premolar and highest vertical forces at the first premolar and first molar brackets. Highly significant differences between moments of these two types of archwires and other tested alloys were found. In contrast to other wires, Gummetal, TMA, and Blue Elgiloy multiloop performed the same at room and body temperature.

3.7. Calorimetric and Thermomechanical Properties. Gummetal, TMA, Copper NiTi (CuNiTi), Thermalloy Plus, Nitinol SE, and NiTi wires were subjected to a dynamic mechanical analysis and differential scanning calorimetry by Laino et al. [22]. A model was designed to predict the elastic modulus of superelastic wires. Gummetal and TMA presented a flexural elastic modulus almost constant with the temperature. On the contrary, the elastic modulus of the Thermalloy Plus, NiTi, Nitinol, and CuNiti were temperature dependent. It was stated that Gummetal wire behaved as an elastic wire with a very low Young's Modulus (40 GPa +/-3 GPa) which was about half of that related to TMA (105.0+/-8.5 GPa).

4. Discussion

β-Ti alloys are important class of alloys that have found use in demanding applications such as aircraft structures, engines, orthopedic, and orthodontic implants [23]. Their high strength, great biocompatibility, excellent corrosion resistance, and ease of fabrication provide important advantages compared to other high performance alloys [23]. It was stated by Suzuki et al. [13] that mechanical properties vary markedly among β-Ti wires from different manufacturers. Thus, it seems that understanding their specific properties is essential for proper clinical application [13].

Gummetal unveils unique mechanical properties and combines them with typical for β-Ti alloys lack of toxicity due to nickel and chromium-free chemical composition [6]. Clinicians should be aware of possible adverse reactions arising from the intraoral use of orthodontic materials due to corrosion, galvanic corrosion, and release of ions from different alloys [24]. TiNb wires could substitute CoCr, SS, and NiTi archwires in particular stages of orthodontic treatment especially, but not only, in susceptible groups of patients [25–27].

Nordstrom et al. [10] claimed that further studies are necessary to evaluate the usefulness of Gummetal with different wire sizes and in various clinical situations in order to prove its advantages over other wires. They also suggested that Gummetal wire could be used in patients when bends could be useful from the beginning of orthodontic treatment.

According to Grauberger [12], advertised "superelasticity" of Gummetal should be discussed and examined in the future.

Orthodontists should be aware of the FFs in bracket-wire combinations to achieve efficient tooth movement [12]. Kopsahilis [16] mentioned that additional in vivo tests with oral mouth conditions might have significant influence on FF rankings of orthodontic wires.

Gentle and continuous load is desired for optimal tooth movement [28]. Gummetal orthodontic archwire could be useful for the initial stage of orthodontic treatment but might be convenient in the final stage as well [22].

The search for an ideal orthodontic wire definitely has not come to an end yet [29]. There are many different methods and tests, including more 3-dimensional finite element model analyses, low-level laser therapies, and biochemical or spectroscopic analytical methods which could be performed to compare the characteristics of novel orthodontic wires with the older existing ones [30–34]. Surprisingly, for the authors of this review, from 2003 when there were first publications about the great potential of Gummetal alloy up to date, to the best knowledge of authors, only one double-blind RCT exists in the literature available to compare its usefulness as orthodontic archwire with dissimilar wire.

5. Conclusions

(i) Gummetal archwire could be useful in the initial stage of orthodontic treatment alternatively to NiTi wires. However, it shows some plastic deformation, which questions its superelasticity

(ii) It is assumed that Gummetal alloy could be used in patients suffering from nickel allergy; all the atomic elements of the alloy are nontoxic and biocompatible

(iii) Gummetal wire exhibits low bending strength, low fatigue limit, and high resilience. However, these properties do not affect the numbers of cycles to fracture (similar risk to wire fracture)

(iv) Loss of applied force due to friction of Gummetal wire is comparable to SS and CoCr wires

(v) TiNb wires might demonstrate appropriate torque moment and low tension values when they are used combined with edgewise appliances (GEAW technique)

(vi) Gummetal archwire has a very low Young's Modulus constant with the temperature with high tensile strength, which provides lower force than Nitinol and TMA but higher than Supercable wire

Abbreviations

β-Ti:	β-Titanium
CoCr:	Cobalt-chromium
CuNiTi:	Copper nickel-titanium
FF, FFs:	Frictional force(s)
GEAW:	Gummetal edgewise archwire
MEAW:	Multiloop edgewise archwire
NiTi:	Nickel-titanium
RCT:	Randomized clinical trial
RoB:	Risk of bias
SS:	Stainless steel
Ti:	Titanium
TiMo:	Titanium-molybdenum
TiNb:	Titanium-niobium, Gummetal
TNTZO:	Titanium-niobium-tantalum-zirconium-O, Gummetal.

Data Availability

DOI links are available where applicable in the references. The rest of positions in the reference list are books, articles without DOI number (Japanese, German, Spanish), and PhD dissertations available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors' Contributions

Krzysztof Schmeidl contributed to the design of the research, to the analysis of the results, and to the writing of the manuscript. Joanna Janiszewska-Olszowska designed and directed the project and contributed to the writing of the manuscript. Katarzyna Grocholewicz supervised the project. All authors read and approved the final manuscript.

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Article

Frictional Properties of the TiNbTaZrO Orthodontic Wire—A Laboratory Comparison to Popular Archwires

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Abstract: Background. This study aimed to determine the kinetic frictional force (FF) of the recently produced TiNbTaZrO (Gummetal) orthodontic wire and compare it to the widely used wires of stainless steel (SS), nickel-titanium (NiTi), cobalt-chromium (CoCr) and titanium-molybdenum (TiMo) alloys. Methods. Five types of 0.016″ × 0.022″ wires were ligated with elastic ligatures to 0.018″ × 0.025″ SS brackets. The dynamic FFs between the brackets and ligated wires were measured utilizing a specialized tensile tester machine. Prior sample sizes for different archwires were conducted using power analysis for the general linear models. The existence of significant differences in FF between examined materials was initially confirmed by the one-way analysis of variance (ANOVA) with further evidence of pairwise differences by Tukey's Honest Significant Difference test. Results. The pairwise differences between means of kinetic FFs for NiTi, CoCr, and Gummetal wires were not statistically significant (adjusted *p*-value > 0.05). Stainless steel alloy presented the lowest FF values significantly different from other groups (adjusted *p*-value < 0.05). On the contrary, TiMo wires showed significantly greater FFs (adjusted *p*-value < 0.05) than other alloys. Conclusions. Gummetal orthodontic wire exhibits similar frictional resistance as NiTi and CoCr wires. Bendable TiNbTaZrO wire might be used for sliding mechanics due to its favorable frictional properties.

Keywords: Gummetal; dynamic friction; TiNb; orthodontic archwire

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Citation: Schmeidl, K.; Wieczorowski, M.; Grocholewicz, K.; Mendak, M.; Janiszewska-Olszowska, J. Frictional Properties of the TiNbTaZrO Orthodontic Wire—A Laboratory Comparison to Popular Archwires. *Materials* **2021**, *14*, 6233. https://doi.org/10.3390/ma14216233

Academic Editor: Francesco Inchingolo

Received: 21 August 2021
Accepted: 17 October 2021
Published: 20 October 2021

1. Introduction

Friction is the force that opposes motion between any surfaces that are in contact [1]. Frictional force (FF) in orthodontics occurs at multiple contact points along the bracket-archwire interface during multibracket treatment. Brackets bonded on different tooth surfaces transfer forces to teeth [2,3]. Orthodontic tooth movement depends on static and dynamic friction [4]. Sliding between wire and bracket in the oral cavity occurs at a low velocity. Variables affecting friction between the components of multibracket appliances are related to the type of archwire, the bracket, the ligation system, and biological factors [5,6].

Different alloys are used for producing orthodontic wires required in the active phase of orthodontic treatment. Clinicians should be aware of frictional resistance of archwires, especially during *en masse* movement or canine retraction. When sliding mechanics are utilized, FF is generated between the wire, bracket, and ligature, impeding tooth movement during the phase of retraction and transmitting forces to the posterior teeth. These forces negatively affect the anchorage requirement, potentially resulting in loss of anchorage [7]. The ideal orthodontic wire should provide a low coefficient of friction to move the teeth efficiently and freely.

Stainless steel (SS) wires are widely known for their high stiffness and low friction properties compared to other archwire materials [8]. The use of a combination of SS archwires and brackets has been the gold standard for orthodontists to utilize during sliding mechanics. Stainless steel archwires are also considered the reference material for assessing the mechanical properties of newly fabricated archwires [9,10].

Cobalt-chromium (CoCr) wire emerged in the 1960s [11]. One advantage of using it for orthodontic applications is its low hardness. After being shaped, the CoCr archwire can be hardened by heat treatment, which substantially increases its strength. For years, SS and CoCr alloys were the standards in orthodontic treatment.

Nitinol was developed in the early 1960s and introduced to orthodontics in the late 1970s [12]. Orthodontic nickel-titanium (NiTi) wires are widely used. They have simplified the initial phase of orthodontic treatment due to their low forces over a wide range of activation and superelastic properties [13]. However, the low deformability of NiTi archwires limits their use in the final phases of orthodontic therapy.

Titanium-molybdenum (TiMo) is a beta-titanium (β-Ti) alloy introduced to orthodontics in the 1980s. It combines high strength and springiness, making it a good choice for finishing (especially rectangular wires used in the late stages of multibracket orthodontic treatment). Beta-titanium lacks the stiffness and formability of CoCr; however, it is not suitable for applications that require the flexibility of an archwire. Another drawback of TiMo wires is their high surface roughness, which produces high friction between the bracket and archwire [14]. The development of new β-Ti wires and other titanium alloys has rapidly increased recently, partly because of the high biocompatibility of these nickel and chromium-free archwires [15].

In previous studies of frictional resistance of orthodontic wires, TiMo wires generated the highest friction values, followed by NiTi and SS wire, when using the SS brackets [16]. Another study stated that SS wires performed the least amount of friction, followed by CoCr, NiTi, and β-Ti wires [17].

Gummetal is a recent multifunctional β-Ti alloy. It consists of titanium, niobium, tantalum, zirconium, and oxygen (TiNbTaZrO), making it bioinert [18–20]. The abovementioned metals are placed in groups IVa and Va of the periodic table of elements. Gummetal was developed in 2001 at the Metallurgy Research Section of Toyota Central R&D, Inc. in Japan [21]. The chemical composition of Gummetal (Ti-23Nb-0.7Ta-2Zr-1.2O) was based on atomic valence theory. To achieve its rare characteristics, the alloy is intensively cold-worked. Special characteristics of Gummetal arise from the juxtaposition of electronic magic numbers: Bo value of 2.87, compositional average valence electron number of 4.24, and Md value of 2.45 eV [22]. According to Hasegawa, Gummetal wire can reduce friction between the archwire and metal brackets by up to 50% compared with other titanium wires [22]. It exhibits a very low Young's Modulus constant with the temperature and high tensile strength (which is extremely rare) and provides lower force than NiTi and β-Ti archwires. Manufacturers state that the dislocation motion of the crystal (plastic deformation) is controlled completely, which makes Gummetal unique [23].

The authors of this research have found only a single article comparing the FFs of Gummetal, NiTi, and TiMo orthodontic wires [24]. Besides, in their recently published review, the present study's authors have not found any published studies comparing FFs of Gummetal with other conventional wires [25]. Thus, the objective of this study was to determine the kinetic FFs of Gummetal wire and compare them with the abovementioned well-known archwire alloys.

Although according to the theory, the FF is not directly related to the surface, the authors decided to analyze the topography of all five orthodontic wires. Materials were intentionally placed in contact, and the nature of the contact is linked directly to the layout of surface asperities, which is the subject of functional surface analyses in many areas of science [26,27].

2. Materials and Methods

In the present study, 50 SS brackets (Discovery, Dentaurum) with declared slot sizes of 0.018 × 0.025″ (0.018″ slot) and Roth prescription for the maxillary right canine were used. Five types of 0.016 × 0.022″ 10 cm long straight wires (n = 50), including (ten specimens each): SS (Remanium, Dentaurum, Ispringen, Germany), CoCr (Elgiloy Blue, RMO, Denver, CO, USA), NiTi (Nickel Titanium, G&H, Franklin, IN, USA), TiMo (BetaForce, Ortho Technology, West Columbia, SC, USA), and TiNbTaZrO wires (Gummetal, JM Ortho Corporation, Tokyo, Japan) were ligated to the brackets with elastic modules (Alastik Easy-To-Tie, 3M, Saint Paul, MN, USA).

Each bracket was bonded on a steel plate S235JR 1,4 mm thick, 50 mm wide, and 115 mm long, using cyanoacrylate adhesive (Kemsin KC-1200, Chemkon). Bracket prescription characteristics were minimized by supporting the bracket with a 0.018 × 0.025″ SS straight wire jig (Remanium, Dentaurum). The jig was removed once the adhesive had hardened. All the bonding procedures, for standardization purposes, were carried out by the same operator. The measurement condition was taken at a dry state at room temperature. Then, each wire was ligated to the bracket with elastic ligature so that the lower, shorter end of the wire was left free.

Following the bonding and ligating procedures, each model was mounted in the base handle of the MultiTest 2.5-i testing machine (Mecmesin Ltd., Horsham, UK) (Figure 1). The steel plate was placed in the handle of the machine and then fixed with straight wire perpendicular to the machine's base and parallel to the bracket's slot.

Figure 1. A model mounted in the base handle of the force testing machine.

Afterward, 10 mm of the upper end of the wire was fixed to the special tension-loading cell of the tensile measuring machine with a range of up to 10 N loadcell capacity and full-scale accuracy of ±0.1%. Subsequently, the wire was pulled through at a crosshead speed of 10 mm/min for a distance of 20 mm. The machine was recording 1000 measurements of FF per second. The kinetic FF was measured by averaging the FFs exerted during the 120 s long-lasting wire movement. Recorded measurements of dynamic FF for each of 50 wire-ligature-bracket combinations were then saved on a PC employing Emperor (Mecmesin Ltd.) force testing software.

The statistical analysis was undertaken using IDE version 1.4.1106 (RStudio) and R version 4.0.4 (R Core Team) software. For the prior sample size estimation, the authors used power calculations for the general linear models. Assuming the degrees of freedom for the numerator u = 4 (for 5 groups), effect size f2 = 0.4 (we used a medium value for a priory testing), a significance level of 5%, and large power value = 0.75, the total sample size for the present experiment should have equaled at least 48, thus having 10 samples per group met the conditions [28,29].

To carry out a statistical analysis of the data, the authors have proceeded from two classical hypotheses:

- A null hypothesis: there is no difference in kinetic FF between groups.
- The alternative hypothesis proposes that there is a difference at least between one pair of groups.

Several statistical tests were performed to test the hypotheses. However, some tests were designed to work with small or medium size samples (up to 5000). Therefore, when performing statistical tests, the mean values of the sample groups were used instead of the whole groups of samples. The use of sample means was justified because each data distribution group, as seen in the next section, generally corresponded to the normal one.

A one-way analysis of variance (ANOVA) has been performed to determine if there were differences between the groups. ANOVA is an extension of independent two-samples *t*-test for comparing means in a situation where there are more than two groups.

However, the ANOVA test is based on the assumptions of the homogeneous variance across groups and the normally distributed data. Levene's test for group homogeneity estimation has been used to check the first assumption. This test is less sensitive to departures from normal distribution compared to Bartlett's test [29]. For checking the second (normality) assumption, the Shapiro–Wilk's test on the ANOVA residuals has been performed.

A general linear hypothesis test was applied to specify between which group of samples, potentially, there were statistical differences in kinetic FFs.

In order to demonstrate the differences visually, the post hoc Tukey's Honest Significant Difference (HSD) test was performed. That test relies on a set of confidence intervals on the differences between the means of the levels of a factor with the specified family-wise probability of coverage. The intervals were based on the studentized range statistic, Tukey's HSD method.

There are many methods for measuring surface topography, divided into two main groups: contact and contactless. Since it is difficult to achieve consistency between methods using different physical principles [30], it was decided to use a focus variation microscope with an appropriately selected lighting system [31], as shown in Figure 2.

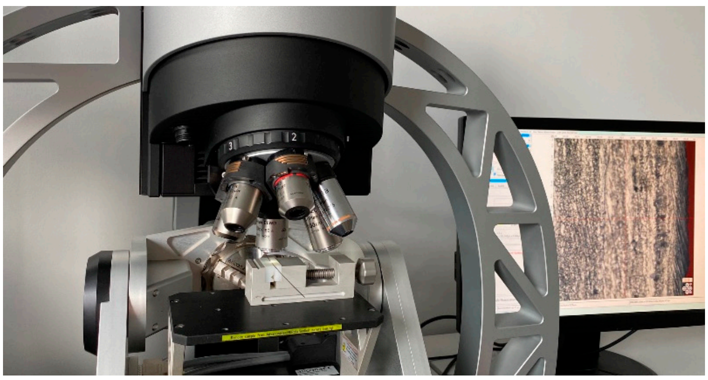

Figure 2. A focus variation microscope used for topography measurements with a wire in a holder.

Focus variation microscopy sharpens the surface image to measure the surface unevenness. The measured object is illuminated by light with appropriate modulation, transmitted by optics, and focused on the surface. The reflected light returns through the optical system and reaches the digital detector searching for the focus beam. The surface image is shaped by an optical system capable of obtaining both photometric (brightness, color, etc.) and geometric (distances, shape) information [32]. For the surface topography reconstruction, only those places where the data from the detector coincide with the data from the focus area will be stored.

In the present study, the measurements were made for representative samples of each material utilizing Alicona IF G5 focus variation microscope. After obtaining raw measurement data, a procedure was carried out to fill in non-measured points, which could be problematic with many optical measurements [33]. Subsequently, the shape was then removed by a third-degree polynomial and filtration of the surface waviness employing the Gaussian filter. A cut-off (compliant with a nesting index) of 0.25 mm was used. For measurements, 50× magnification was chosen with coaxial illumination (no polarization), 20 nm vertical resolution, and 2.15 µm horizontal resolution. Sampling distance was equal to 0.176 µm with a total measurement area of 2.629 mm × 0.611 mm.

3. Results

The distribution of the kinetic FFs by the samples compared has been presented in Table 1.

Table 1. Distribution of the kinetic FF by the groups of samples (unit; N).

Group [1]	Mean	SD	Median	TM [2]	Min	Max	Skew	Kurtosis	SE	IQR	Q1	Q3
Remanium (SS)	0.639	0.139	0.640	0.628	0.216	1.446	1.693	6.502	<0.0001	0.141	0.548	0.689
Nickel-Titanium (NiTi)	1.143	0.306	1.087	1.114	0.005	2.319	1.020	1.508	<0.0001	0.399	0.917	1.316
Elgiloy Blue (CoCr)	1.097	0.354	1.014	1.078	0.011	2.267	0.409	−0.932	<0.0001	0.569	0.813	1.382
BetaForce (TiMo)	1.932	0.307	1.930	1.934	0.152	2.839	−0.138	0.253	<0.0001	0.431	1.727	2.158
Gummetal (TiNbTaZrO)	1.198	0.208	1.181	1.192	0.129	1.694	0.192	0.060	<0.0001	0.244	1.064	1.308

[1]—Sample size per group n = 1,200,000. [2]—Trimmed mean.

That being the case, the Remanium's and Gummetal's interquartile ranges (IQRs) are comparatively narrow. This suggests that overall data have a high level of agreement with one another. On the contrary, Elgiloy data is the most dispersed. Additionally, Remanium and BetaForce medians do not intersect with other group's IQRs, then there are differences between these groups. Medians for Nickel-Titanium, Elgiloy Blue, and Gummetal lie within one another's IQR boundaries.

All groups have bell-shaped (unimodal) histograms, except Nickel-Titanium, which has a bimodal one. Positively skewed histograms describe Remanium and Nickel-Titanium with highly and moderately kurtosis, respectively. Also, kurtosis but a negative one is present on Elgiloy Blue histogram. The values of asymmetry and excess for BetaForce and Gummetal groups of samples are insignificant; moreover, these groups have the lowest SDs.

Initially, based on the analysis of descriptive statistics, the values for BetaForce, Gummetal, and Remanium respectively most closely satisfy the criteria for normal distributions.

Figure 3 presents the FF distribution data for each group as a histogram. A normal distribution curve was superimposed with mean and standard deviations (SDs) from Table 1 to visualize and assess how the histograms deviated from a normal distribution.

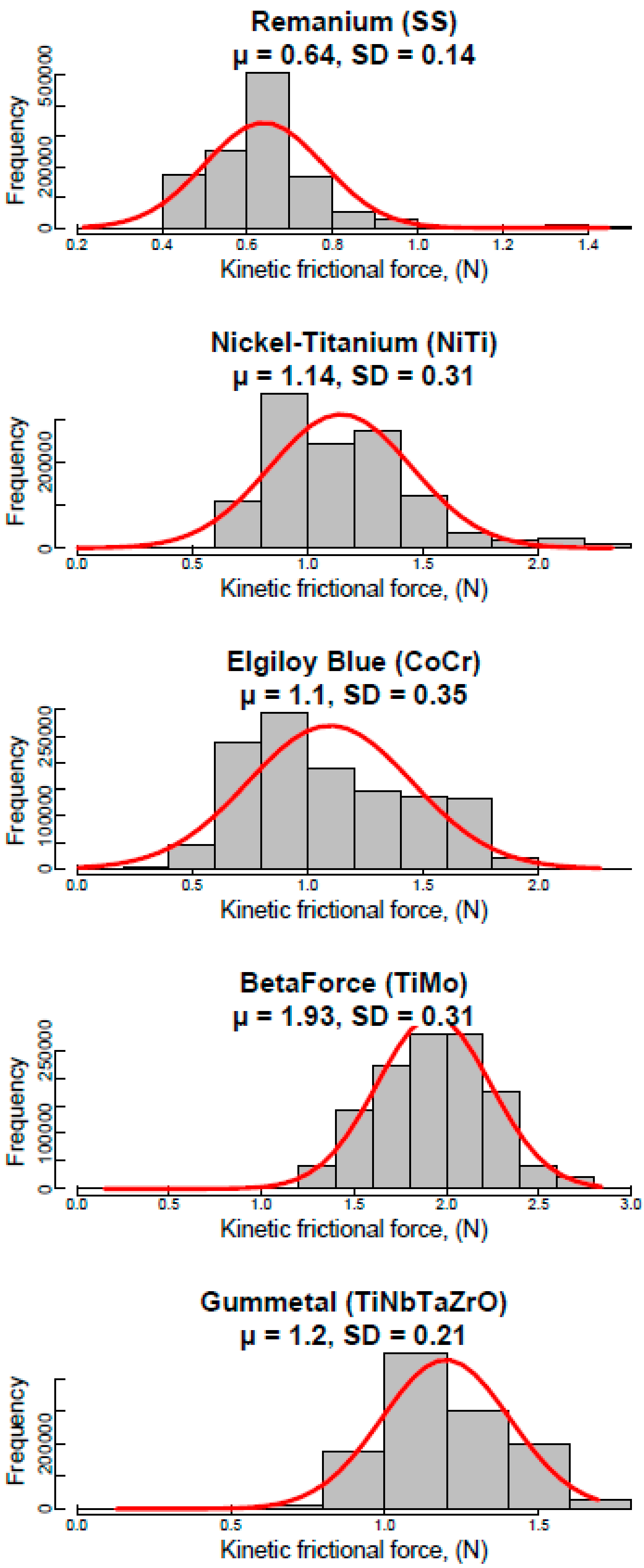

Figure 3. Histogram with normal curve per group of samples (*n* = 1,200,000) presenting the empirical distribution of kinetic FF (unit; N).

In general, there are some deviations from the normal distribution. However, due to the very large sample size (n = 120,000) and 10 independent samples in each group, the influence of outliers' presence remains negligible. The mean values of the sample groups used to perform statistical tests are presented in Table 2.

Table 2. Descriptive statistics of kinetic FF by group sample means (unit; N).

Group	Sample									
	1	2	3	4	5	6	7	8	9	10
Remanium (SS)	0.45	0.88	0.5	0.61	0.64	0.72	0.55	0.73	0.65	0.65
Nickel-Titanium (NiTi)	1.35	1.04	0.94	0.93	1.31	1.66	0.84	0.91	1.06	0.86
Elgiloy Blue (CoCr)	0.86	1.47	1.03	0.99	1.49	0.64	1.22	1.24	1.24	0.79
BetaForce (TiMo)	1.94	1.81	2.26	2.03	2.03	1.71	1.8	1.93	2.1	1.71
Gummetal (TiNbTaZrO)	1.11	1.25	0.97	1.08	1.47	1.17	1.06	1.51	1.21	1.14

Summarizing the analysis of variance group sample means is given in Table 3.

Table 3. One-factor ANOVA results.

Df	Sum Sq	Mean Sq	F Value	Pr (>F)	Df
Group	4	8.645	2.1612	47.13	1.55×10^{-15}
Residuals	45	2.063	0.0459	-	-

Because the p-value is less than the significance level of 0.05, it indicates the differences between the groups.

The results of Levene's test have been presented in Table 4.

Table 4. Levene's test summary. Defining the homogeneity of variances.

Group Variable	Df1	Df2	F-Value	Pr (>F)
Group	45	4	2.236	0.08

The test reveals a p-value greater than 0.05, indicating no significant difference between the group variances. Therefore, the homogeneity of variances in the different groups has been confirmed.

The result of the Shapiro–Wilk's test output obtained W = 0.98355, p-value = 0.7078, so far as p-value is greater than 0.05, hence, no indication that normality is violated.

Based on the results of a one-way ANOVA test along with Levene's and Shapiro–Wilk's tests, it can be assumed that there is a difference in kinetic FFs between some groups. To specify between which ones, a general linear hypothesis test was applied (Table 5).

According to the data in Table 5, a statistical difference is significant for groups with Pr(>|t|) less than the p-value (0.05).

Confidence intervals estimated by performing the post hoc Tukey's HSD test are presented in Figure 4.

Data presented in Figure 4 report that three out of ten pairwise group differences (where confidence interval crosses the dotted line containing zero) are considered non-significant.

Based on the information regarding Pr(>|t|) from Table 5, lower and upper confidence interval values from Figure 3, results of the statistical significance of the differences between the sample group means are presented in Table 6.

Table 5. Defining the homogeneity of variances. Results of simultaneous tests for general linear hypotheses.

Pairwise Group Comparison	Difference *	*t*-Value	Pr(>|t|)
Elgiloy Blue (CoCr)—BetaForce (TiMo)	−0.83522	−8.722	<0.0001
Gummetal (TiNbTaZrO)—BetaForce (TiMo)	−0.73392	−7.664	<0.0001
Nickel-Titanium (NiTi)—BetaForce (TiMo)	−0.78896	−8.239	<0.0001
Remanium (SS)—BetaForce (TiMo)	−1.29306	−13.503	<0.0001
Gummetal (TiNbTaZrO)—Elgiloy Blue (CoCr)	0.10130	1.058	0.826769
Nickel-Titanium (NiTi)—Elgiloy Blue (CoCr)	0.04626	0.483	0.988543
Remanium (SS)—Elgiloy Blue (CoCr)	−0.45784	−4.781	0.000196
Nickel-Titanium (NiTi)—Gummetal (TiNbTaZrO)	−0.05504	−0.575	0.978098
Remanium (SS)—Gummetal (TiNbTaZrO)	−0.55914	−5.839	<0.0001
Remanium (SS)—Nickel-Titanium (NiTi)	−0.50409	−5.264	<0.0001

*—the pairwise difference between sample group means.

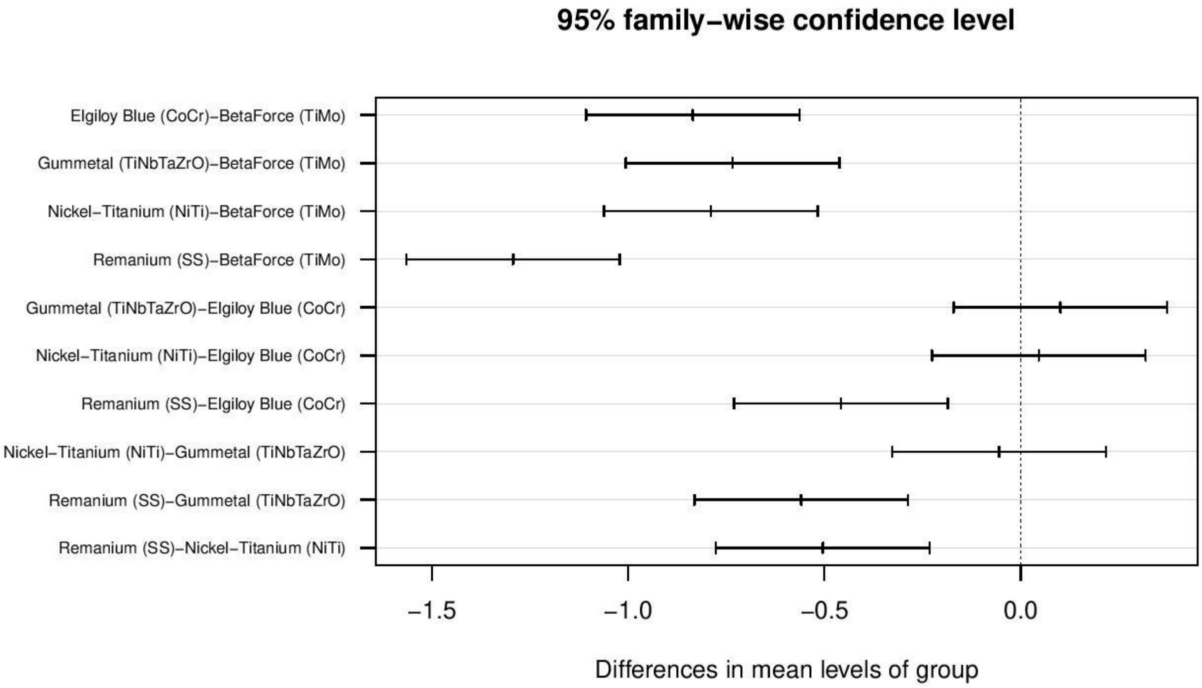

Figure 4. Pairwise group means differences in the form of confidence intervals.

Table 6. Presence (+)/absence (−) of statistically significant differences between the sample group means (p-value < 0.05).

Orthodontic Wire	Remanium (SS)	Nickel-Titanium (NiTi)	Elgiloy Blue (CoCr)	BetaForce (TiMo)	Gummetal (TiNbTaZrO)
Remanium (SS)		+	+	+	+
Nickel-Titanium (NiTi)	+		−	+	−
Elgiloy Blue (CoCr)	+	−		+	−
BetaForce (TiMo)	+	+	+		+
Gummetal (TiNbTaZrO)	+	−	−	+	

Seven out of ten pairwise group comparisons turned out to be statistically significant. Remanium and BetaForce group sample means both showed a significant difference between each other and between all the other groups. On the other hand, no statistically significant differences were found between pairwise comparisons of Nickel-Titanium, Gummetal, and Elgiloy Blue sample group means. Among the studied groups, the lowest values of kinetic FFs were exerted by Remanium, the highest ones—by BetaForce; the medium forces were shown by Elgiloy Blue, Nickel-Titanium, and Gummetal.

A topographical analysis of wires from the compared materials was also carried out. The images of each of them, together with their topographical maps, are shown in Figure 5.

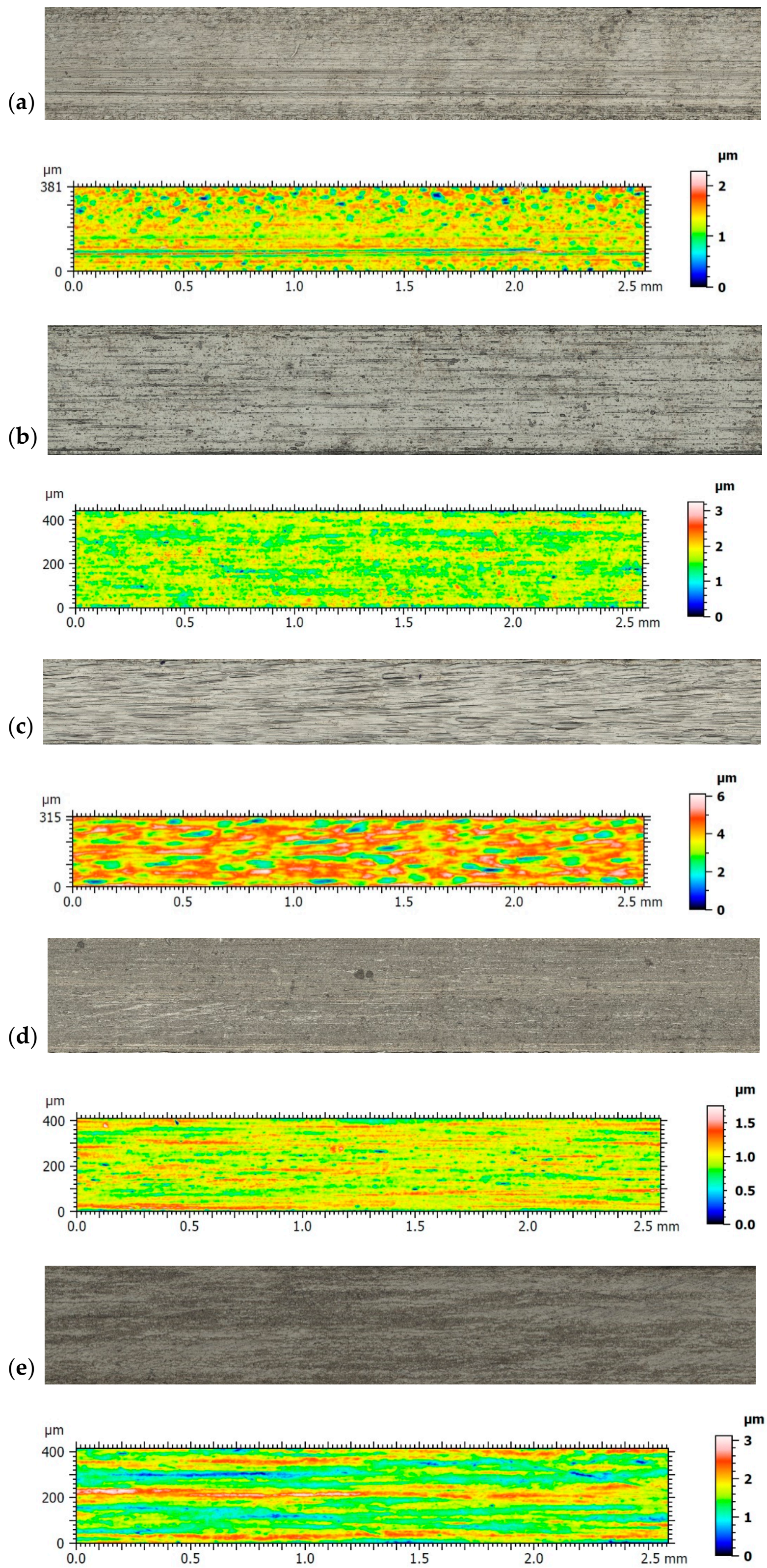

Figure 5. Images of different wires: (**a**) Remanium (SS); (**b**) Nickel-Titanium (NiTi); (**c**) Elgiloy Blue (CoCr); (**d**) BetaForce (TiMo); (**e**) Gummetal (TiNbTaZrO).

Results of topography and roughness parameters are presented in Table 7.

Table 7. Surface parameters for wires made from different materials.

Orthodontic Wire	RSm µm	Sq µm	Ssk -	Sz µm	Sk µm	Spk µm	Svk µm	Smr1 %	Smr2 %
Remanium	31.0	0.26	−0.72	2.28	0.56	0.20	0.39	8.5	85.0
NiTi	30.8	0.27	−0.68	3.25	0.62	0.22	0.39	7.7	86.3
Elgiloy Blue	42.7	0.89	−0.48	6.10	2.33	0.45	1.08	6.5	88.1
BetaForce	25.3	0.16	−0.41	1.75	0.36	0.16	0.22	10.5	88.9
Gummetal	33.0	0.41	0.14	3.11	1.07	0.44	0.37	10.4	91.3

All the parameters were evaluated according to ISO 4287 [34] and ISO 25178 [35]. The following parameters were presented:

RSm—mean width of the roughness profile elements
Sq—root mean square height of the scale-limited surface
Ssk—skewness of the scale-limited surface
Sz—maximum height of the scale-limited surface
Sk—core height
Spk—reduced peak height
Svk—reduced dale height
Smr1—material ratio at the intersection line separating hills from the core surface
Smr2—material ratio at the intersection line separating dales from the core surface

4. Discussion

Friction in orthodontic therapy is a considerable clinical challenge, which must be well controlled and understood considering that it cannot be eliminated from the multibracket treatment. Using materials providing lower levels of friction reduces the force lost during the sliding of orthodontic wire. Thus, forces transmitted to the periodontal ligament are decreased, and overloading might be avoided [36].

The frictional force is a part of the resistance to sliding (RS), such as when a bracket moves along an archwire during orthodontic therapy. Kusy and Whitley [37] divided RS into three components: FFs, due to contact of the bracket surfaces and wire; binding, which is created when the archwire flexes or the tooth tips and contacts between the wire and the bracket corners occurs; and notching, when plastic deformation of the wire cross-section happens at the bracket-wire corner interface, which often takes place in clinical situations. In the study by Nishio et al. [38] the values of FF were directly proportional to the angulation increase between the wire and the bracket. Orthodontists should be well aware of all the factors influencing efficient tooth movement.

In a single study investigating frictional properties of Gummetal found, Takada et al. [24] reported that TiMo exhibited significantly higher frictional values than Gummetal and that NiTi archwires showed comparable frictional characteristics to TiNbTaZrO alloy. Similar results have been reported in the present study.

Alfonso et al. [39] reported that the frictional resistance is affected by the hardness of archwire alloys and published results that present a linear relationship between the hardness of different archwire alloys and the friction coefficients. These findings indicate that the frictional resistance of Gummetal wire might be slightly greater because of its lesser hardness and lower elastic modulus compared to NiTi archwire [24].

In the current work, the authors decided to use conventional elastomeric ligatures as the ligation method. As in previous similar studies, elastic ligatures were placed immediately before the tests, with no decay caused by exposure to time or a humid environment [40]. This approach provides impartial and comparable conditions for testing FFs in vitro [41,42].

In the present study, care was taken to place each bracket in a position so that the bracket slot was passive with respect to 0.016 × 0.022″ straight wires mounted on a steel plate. However, the authors are aware that minor non-linearity of the wire and malalignment of the orthodontic bracket could not be fully controlled and might have affected obtained results.

It is known that bracket sets, series, and single brackets are characterized by imperfections [43] that might affect the bracket slot's structure, dimensions, roughness, and shape, e.g., divergence, convergence, parallelism, and rounding off their inner walls [44,45]. If contact between bracket and archwire is looser and smoother, friction is reduced; on the other hand, tight contact and rougher surface result in increased friction values [42]. Moreover, differences exist between declared and actual orthodontic bracket slot sizes [43,44]. Thus, fifty brackets from one producer were used in this experiment to improve the statistical control by decreasing the impact of confounding variables.

Each of the 50 tests performed in the present study comprised a new section of a wire and a new bracket to avoid mechanical wear signs of the brackets or the wire. Drawing a wire through the bracket results in a plastic displacement of the surface and the near-surface material and the detachment of particles responsible for wear debris [46]. Thus, using one bracket for many tests might have influenced obtained FFs results.

Forces needed to overcome friction in vitro are higher than those in vivo, as claimed by Ho and West [47]. Lubrication plays a role in reducing FFs between brackets and wires during in vitro tests with different types of human and artificial saliva [48]. This fact might be a possible limitation of the present in vitro study performed in dry conditions. Fortunately, in vitro studies of archwires performed in dry conditions present rankings of FFs and order of frictional values similar to wet conditions and can provide orthodontists valuable and relevant clinical information [37]. On the other hand, it is difficult to be completely certain how precisely laboratory equipment could recreate the same in vivo situation with the response of periodontal ligament to orthodontic forces [49]. At the moment, tooth movement cannot be completely imitated in vitro [36,50].

The topographic analysis of the surfaces showed that the Gummetal archwire did not deviate from the others in fundamental respects. All wires after processing presented a periodical structure, which was depicted by the values of RSm parameters. Their variability exhibited a change in machining parameters while maintaining the process. The greatest asperities occurred for Elgiloy Blue, as shown by the amplitude values of the mean (Sq) and maximum (Sz) parameters. These values were several times higher than those obtained for BetaForce, which in turn were the smallest. The difference with Gummetal was that a positive value of skewness (Ssk) was obtained, with negative values for other materials. That demonstrated the slight domination of individual, high peaks over the valleys. However, these differences were not substantial, and one has to bear in mind the stochastic component. The last group of analyzed parameters was obtained from the material ratio curve. These parameters [51] are commonly used for assessing contact surfaces subject to the wear process. Here, also for Gummetal wire, the authors found confirmation of the domination of peaks over valleys, as the Spk was larger than Svk. For other materials, this relationship was reversed. The surfaces presented generally poor properties for maintaining the lubricating medium, which can be observed from the low values of Svk in relation to Sk. The relatively high value of Smr2 also shows the low impact of the valleys for Gummetal. However, all the parameters presented are similar in nature for all the materials analyzed, making future wear tests independent of topography.

5. Conclusions

Gummetal wire unveiled similar frictional resistance as the CoCr and NiTi archwires. The frictional properties presented by Gummetal alloy were superior to the TiMo but inferior to the SS alloy wire. There are no significant differences in surface topography for different materials, which will make the wear test much more reliable. More in vitro and in vivo studies are necessary to find the best use for Gummetal archwire in orthodontic treatment.

Author Contributions: Conceptualization, J.J.-O. and K.S.; methodology, K.S. and J.J.-O.; software, K.S. and M.M.; validation, K.S. and M.W.; formal analysis, K.S. and M.W.; investigation, K.S.; resources, K.S. and J.J.-O.; data curation, K.S.; writing—original draft preparation, K.S.; writing—review and editing, J.J.-O. and M.W.; visualization, K.S. and M.M.; supervision, K.G.; project administration, K.G. All authors have read and agreed to the final version of the manuscript.

Funding: This research received no external funding. This study was self-funded.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

FF(s)	frictional force(s)
TiNbTaZrO	Gummetal
SS	stainless steel
NiTi	nickel-titanium
CoCr	cobalt-chromium
TiMo	titanium-molybdenum
β-Ti	beta-titanium
IQR(s)	interquartile range(s)
SD(s)	standard deviation(s)
HSD	Honest Significant Difference
RS	resistance to sliding

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